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## **Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) Thermography Diagnostic for Building Envelopes**

Camp Lejeune, NC

James P. Miller and Navi Singh

August 2015



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# **Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) Thermography Diagnostic for Building Envelopes**

Camp Lejeune, NC

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## **Abstract**

Each year, U.S Department of Defense buildings waste millions of dollars' in energy lost through leaks in building envelopes. Identifying the source of this wasted energy has historically been time consuming and prohibitively expensive for large-scale energy analysis. This work used an independently developed drive-by thermal imaging solution that can enable the Department of Defense (DoD) to achieve cost-effective energy efficiency at much greater scale than other commercially available techniques of measuring energy loss due to envelope inefficiencies from the built environment. A multi-sensor hardware device is attached to the roof of a customized vehicle to rapidly scan hundreds of buildings in a short period of time. At U.S. Marine Corps Base Camp Lejeune, the unit identified over 2500 distinct building feature components identified across various buildings throughout the base. These features were categorized by type and surface temperature to provide an in-depth analysis of each building's envelope energy profile. This report includes an in-depth analysis of 30 buildings at each installation, recommends specific energy conservation measures (ECMs), and quantifies significant potential return on investment.

## Executive Summary

Each year, millions of dollars' worth of energy leaks from the envelopes of U.S. Air Force buildings due to missing or improperly installed insulation, cracks around doors and windows, thermal bridges in wall systems and many other deficiencies. Identifying the sources of this wasted energy has historically required manual thermal audits that are typically inconvenient, time consuming, and prohibitively expensive for large-scale energy analysis. Meanwhile, Federal agencies are under immense pressure to dramatically reduce the amount of energy consumed by their buildings.

A unique contractor-developed drive-by thermal imaging solution is available that can enable the Department of Defense (DoD) to achieve cost-effective energy efficiency at much greater scale than other commercially available techniques of measuring energy loss due to envelope inefficiencies from the built environment. A multi-sensor hardware device is attached to the roof of a customized vehicle to rapidly scan hundreds of buildings in a short period of time. The gathered data are processed and analyzed at Essess headquarters to ascertain important building envelope information. This project scanned buildings at U.S. Marine Corps Base Camp Lejeune, NC (ASHRAE Climate Zone 3) to determine the amount of energy being lost at that base due to energy inefficient building envelopes.

Over 2500 distinct building feature components were identified across various buildings throughout the base. These features were categorized by type and surface temperature to provide an in-depth look at the energy efficiency of each building's envelope. This quantified analysis showed that Camp Lejeune could save over \$100,000 per year by implementing ECMs outlined in this report. The total investment would be less than \$1 million, but would allow the base to save nearly \$1.7 million over the lifetime of the measures with a simple payback period of less than 9 years.

This research shows that the use of this technology at Camp Lejeune yields a positive return on investment (ROI). These results are qualified by the fact that Camp Lejeune is located in American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Climate Zone 3. Installations located in colder ASHRAE climate zones (i.e., those with higher "zone" numbers) tend to yield higher potential savings thresholds. The long-term vision of this work is to help the DoD reach its goal of saving energy across all military installations by identifying the best candidate in-

stallations for energy-saving improvements to building envelopes, i.e., those with the highest potential savings. It would be possible to combine that priority list with information on optimal building stocks and portfolios of cost-effective improvements to equip the DoD to save millions of dollars in energy loss.

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## Preface

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The work was managed by the Energy Branch (CF-E) of the Facilities Division (CF) of ERDC-CERL. The ERDC-CERL Principal Investigator (PI) was James P. Miller, CEERD-CF-E. The work, including scanning of buildings at Camp Lejeune, NC, analysis of data and reporting of results was performed by Essess, Boston, MA, under U.S. Army ERDC-CERL contract W9132T-14-C-0002. The following persons and organizations are gratefully acknowledged: (1) The Essess team (Boston, MA), who performed this work under ERDC contract W9132T-14-C-0002, in particular, Mr. Navi Singh, Head of Solutions Delivery, and Mr. Tom Scaramellino, President & Chief Executive Officer, for their tireless efforts and “can do” attitude that helped them to overcome various technical and administrative hurdles to bring this project to a successful conclusion; and (2) personnel from Camp Lejeune, NC. At the time of publication, Mr. Andrew Nelson was Chief, CEERD-CF-E; L. Michelle Hansen was Acting Chief, CEERD-CF; and Kurt Kinnevan, CEERD-CV-T was the Technical Director. The Deputy Director of ERDC-CERL was Dr. Kirankumar V. Topudurti and the Director was Dr. Ilker R. Adiguzel.

COL Jeffrey R. Eckstein was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.



# **1 Introduction**

## **1.1 Background**

According to the FY2012 Base Structure Report, the Department of Defense (DoD) has an existing inventory of 298,897 buildings comprising 2,300 million sq ft. These buildings represent almost every known facility type and range in age from recently constructed buildings to historic buildings more than 100 years old. The size and diversity of this building inventory makes it very difficult to identify and prioritize opportunities to improve building envelopes to reduce energy losses to the exterior ambient environment. It also makes it difficult to verify that building envelope repair/improvement projects have achieved their desired results.

Many Air Force installations are on a scale comparable to villages or small cities, with hundreds or thousands of facilities of various types and ages. Quality and condition of the building envelopes typically range from good to very poor. For most installations, there is significant opportunity to reduce installation energy consumption by identifying and prioritizing opportunities to improve the thermal performance of building envelopes.

Many installations have used infrared thermography as a tool to help identify buildings that have significant energy loss through the building envelope and to pinpoint specific problems on existing building envelopes that might be good candidates for repair or improvement. The U.S. Army Corps of Engineers (USACE) requires infrared scanning of newly constructed buildings prior to turnover to the customer. Unfortunately, although the current state of the handheld thermography technology produces reasonably good results, it is very time consuming to implement. Due to the number of facilities at most Air Force installations, it would be a formidable task to scan more than a small fraction of the facilities. Post-scanning analysis is also very time intensive and highly dependent on the skill of the individuals operating the infrared (IR) camera and interpreting the data. As a result, handheld infrared scanning and analysis methods are too time consuming, not cost-effective for large numbers of buildings, and may yield questionable results.

This project demonstrated a capability to quickly diagnose the condition and thermal performance of building envelopes using Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) thermography to help the U.S. Marine Corps (USMC) identify and implement opportunities to improve the thermal performance of its existing building inventory. The work was conducted at Camp Lejeune, NC. It demonstrated a method of rapidly scanning and analyzing many facilities in a few hours which is far more efficient and cost effective than current methods involving manual infrared thermographic scanning and analysis of facilities. This method produced an accurate and actionable assessment of the assessed installations' facilities that will allow Camp Lejeune civil engineers to optimize use of their limited funds to repair or upgrade building envelopes to reduce installation energy consumption.

Many installations have used infrared thermography as a tool to help identify buildings that have significant energy leakage through the building envelope and to pinpoint specific problems on existing building envelopes that might be good candidates for repair or improvement. USACE requires infrared scanning of newly constructed buildings prior to turnover to the customer. Unfortunately, although the current state of the handheld thermography technology produces reasonably good results, it is very time consuming to implement. Due to the number of facilities at most DoD installations, it would be a formidable task to scan more than a small fraction of the facilities. Post-scanning analysis is also very time intensive and very much dependent on the skill of the individuals operating the IR camera and interpreting the data. As a result, handheld infrared scanning and analysis methods are too time consuming, not cost-effective for large numbers of buildings, and may yield questionable results.

## 1.2 Objectives

The objectives of this demonstration were to:

- *Validate.* This project validated a method of rapidly and cost effectively scanning and analyzing large numbers of building envelopes, quantifying energy losses, and prioritizing energy leaks for cost-effective repairs or improvements.
- *Provide Findings and Guidelines.* This project demonstrated a process by which Civil Engineers can cost effectively evaluate large portions of their building stock to determine the overall condition of their building

- envelopes and identify opportunities to repair or improve the envelopes to reduce unnecessary energy losses and improve overall energy efficiency.
- *Accomplish Technology Transfer:* The Essess imaging rig was deployed based on a licensing model so there was no turnover of hardware, software, or intellectual property to the Government. However, Air Force installations can access this technology by directly contracting with Essess.
  - *Facilitate Acceptance:* This technology is currently marketed as a service to the utilities industry. Essess supports the energy conservation programs of utilities by performing drive-by scanning of large portions of their service areas. This can entail performing scans of tens of thousands of residential or commercial structures. The system software automatically analyzes the thermal imagery and provides a custom report for each building that recommends cost-effective measures to improve comfort, save energy and lower utility costs. In some cases, the utilities may offer the homeowners subsidies or incentives to motivate adoption of recommended measures. Essess may also perform follow-up scans several months after an initial scan to verify that homeowners actually made improvements for which they claimed a credit. In a similar fashion, this technology is a useful tool that can help USMC Civil Engineers evaluate the effectiveness of building repair and renovation projects, and determine if the energy performance of new buildings complies with design requirements.

## 1.1 Regulatory drivers

USMA Civil Engineers face a major challenge of complying with numerous Executive Orders (EO), statutes and DoD/Air Force policies mandating energy consumption reductions in a business climate of reduced installation budgets and manpower. Use of this demonstrated technology may help USMC Civil Engineers comply with the following regulatory drivers:

- *EO 13423 (2007), Strengthening Federal Environmental, Energy, and Transportation Management.* This EO requires Federal agencies to reduce energy use by 20% below their 2003 baseline energy consumption. Reduced energy losses through building envelopes will help installations move toward their energy reduction targets.
- *EO 13514 (2009), Federal Leadership in Environmental, Energy and Economic Performance.* This EO mandates that all new construction, major renovations, or repairs/alterations of Federal buildings comply

with the implications of The Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings (Guiding Principles). The Guiding Principles focus on the following five topic areas for both new construction and major renovations:

1. Employ integrated design principles (new construction)/Employ integrated assessment, operation, and management principles (existing buildings)
  2. Optimize energy performance
  3. Protect and conserve water
  4. Enhance indoor environmental quality
  5. Reduce environmental impact of materials.
- Of these topic areas, the first two might be applicable if the results of a thermographic survey provided an impetus to execute a major renovation of one or more existing buildings.
  - *Energy Independence and Security Act of 2007 (EISA 2007)* requires Federal agencies to conduct and document an energy survey of 100% of their “covered facilities” every 4 years. Although a thermographic survey by itself would not satisfy the EISA 2007 energy survey requirements, it would improve the overall quality of an EISA 2007 survey by providing a quality assessment of the condition of building envelopes.
  - The *U.S. Air Force Energy Strategic Plan* (March 2013) states that the Air Force is pursuing a net zero posture for installation energy and water to help achieve the Federal goal of zero net energy by 2030 for all new facility construction and alterations.
  - Use of this technology may help Air Force Civil Engineers to reduce overall energy use and maximize energy efficiency by identifying and remediating significant energy leaks in existing buildings as part of their operations and maintenance (O&M) program. It may also help installation planners by helping them recognize buildings with such poor building envelopes that a major renovation or outright replacement of the building would be warranted.

## 1.2 Approach

The objectives of this work were accomplished in the following steps:

1. A Kickoff phonecon was conducted with Energy Managers at Camp Lejeune, NC on Thursday, 6 February 2014.
2. Scanning activities at Camp Lejeune were conducted from 10-14 February 2014.

3. Collected data were imported into a secure data storage system located at the contractor's headquarters facility, where the import agent program ran a more rigorous data quality filter. Appendixes to this report contain the following supplemental data:
  - a. Appendix A: Health and Safety Plan
  - b. Appendix B: Points of contact
  - c. Appendix C: Analysis of building components at Marine Corps Base Camp Lejeune, NC
  - d. Appendix D: Detailed Analysis for 30 Buildings at Marine Corps Base Camp Lejeune, NC
  - e. Appendix E: Remediation Cost Estimates
  - f. Appendix F: Collected Data Sample
4. The results were analyzed, conclusions were drawn, and installation-specific recommendations were formulated.

### **1.3 Scope**

Although the results of this work pertain specifically to Camp Lejeune, NC, the technology is considered broadly applicable to all USMC installations.

### **1.4 Mode of technology transfer**

This work demonstrated a capability to quickly and cost effectively perform and analyze scans of USMC installations to identify and prioritize candidate buildings that might benefit from building envelope repairs/improvements. The resulting data will help USMC Civil Engineers to improve the energy performance of their facilities, to reduce energy consumption and utility costs, and to meet mandated energy reduction goals. This project did not transfer hardware, software, or intellectual property to the Government. However, Air Force installations can access this technology by directly contracting with Essess.

## **2 Technology Description**

### **2.1 Technology overview**

#### **2.1.1 Description**

Long-wave infrared (LWIR) cameras are regularly used in conjunction with building audits to identify thermal leaks in building envelopes. Referred to as “infrared thermography,” the technology allows the observer to “see” heat escaping from (or entering) specific areas of buildings. Because objects emit LWIR radiation in wavelengths that vary with their temperature, infrared thermography can help detect problems invisible to the naked eye, including missing, damaged, or improperly installed insulation within walls and roofs, thermal bridges, poor seals, etc. For example, most thermal bridges have a distinctive spatial signature that yields a thermal image with relatively uniformly warm areas surrounded by relatively uniformly cooler areas, separated by a very steep temperature gradient. This data, captured from the street, can be used to locate thermal leaks, determine their extent and, after analysis, their probable underlying cause(s).

Essess is a hardware and software technology company that has developed drive-by thermal imaging capabilities that enable public utility and Government clients to identify energy waste in buildings at an unprecedented scale. In the context of utility projects, the thermal images can be leveraged to deliver the Thermal Analysis Program (TAP), an energy efficiency program that helps public utilities meet mandated state energy efficiency goals by guiding building owners through the process of remediating sources of energy waste. For Government and military projects, the thermal images enable the system to generate a complete analysis of energy waste across the entire building stock, empowering Government and military clients to allocate energy efficiency investments and resources optimally and with greater confidence around the return on investment (ROI).

For military installations, Essess focuses on building envelope analysis and actionable recommendations based on envelope ECMs. A single thermal imaging rig can analyze thousands of buildings in a single night depending on building density and other factors, enabling the system to deliver energy waste intelligence at an order of magnitude greater scale than current



approaches. The patent-pending technology stems from cutting edge research conducted in the Field Intelligence Laboratory at the Massachusetts Institute of Technology (MIT).

This drive-by system uses specially equipped vehicles operating on streets and roadways to capture a 3D thermal video of the surrounding environment. The actual imaging system is a custom-designed multi-sensor rig mounted on the roof of the vehicle. As the vehicle drives, the imaging rig captures the scene on both sides of the car, enabling the system to image large geographic areas each night. The images are stored onboard the vehicle using a custom-built data recording system and then processed at Es-sess' headquarters in Boston, MA. Before analysis, the data are uploaded to Amazon Web Services (AWS) servers housed in nondescript facilities. AWS data centers have industry leading security to ensure the data are protected by military grade perimeter control with state of the art intrusion detection systems.

In an IR thermal image, the brightness of an area indicates its relative energy loss. The brighter the area, the more energy is escaping. Common image patterns demonstrating substantial energy waste include bright yellow lines where siding meets a roof or a chimney, bright yellow or orange auras near foundations, and yellow auras or lines along window or door edges or around soffits. By contrast, a properly insulated building area will appear darker than the surroundings, most commonly blue or purple.

In the context of public utilities, this technology has the capability to generate complete thermal scans of entire utility service territories in a matter of days or weeks. This kind of unprecedented territory-wide analysis would take months or even years using traditional audits, and would likely be prohibitively expensive. This improved thermal scan methodology not only achieves this scale of operation more efficiently and cost effectively, but also with improved accuracy and reliability. While certain information can only be obtained through an in-home audit, the drive-by Thermal Imaging System provides comparable intelligence at an order of magnitude lower cost. Similar results can be expected for buildings on large Government installations. This kind of intelligence is invaluable in determining the buildings that follow-on auditors should survey and also as a pre-diagnostic to make the best use of the auditors' time on site.

### 2.1.2 Components of the system

The drive-by thermal imaging vehicles are equipped with the following components:

- Multi-spectral infrared imaging of structures, including:
  - Long-wave infrared (LWIR) radiometric cameras
  - Near infrared (NIR) high dynamic range cameras
  - NIR scene illumination for rural and poorly lit suburban regions
  - Capture of thermal signatures of structures
- Building façade discovery and background removal capabilities using computer vision and machine learning engines
- A camera housing offering 70 degree vertical field of view and full width horizontal field of view of structures due to vehicle motion
- Automated building detection capability within property boundaries, facilitated by:
  - A rotating laser array light detection and ranging (LIDAR) sensor which captures ranging and reflectance even from large standoff distances
  - A capability to isolate buildings from the scene using 3D LIDAR point clouds
  - A ranging capability which allows structures to be bounded within property lines and relevant locations
  - A mapping grade Global Positioning System (GPS) and support filtering algorithms which ensure highly accurate location of structures and properties
- Collected data used in simultaneous localization and mapping (SLAM), which allows the system to supplement the GPS data captured and more accurately correlate each image to the relevant building.
- Highly reliable onboard data capture and diagnostics system, which includes:
  - Onboard data validation and recording software and hardware
  - Real-time diagnostic and quality control provided by LTE cell network streaming to Essess headquarters
  - A system that performs over a wide range of seasonal temperatures, down to at least -30 °C and up to above 40 °C
- A high mast that enables operation in a variety of regions, including short standoff distances with 3-4 story buildings.

Combined, these hardware and software capabilities constitute a highly effective way to capture heat loss and building envelope data via drive-by thermal imaging (Figure 2-1). Each camera captures data in a video format, meaning that the drive-by system generates hundreds of thousands of images comprising over 2 terabytes of data each night. The LIDAR sensors (Figure 2-2) enable the system to generate a 3D map of the physical environment and map buildings to parcels in a highly accurate manner. The proprietary hardware and software configuration enables the system to capture vast amounts of data and subsequently process that data in a very efficient and automated manner.

Figure 2-1. Specially equipped Essess scanning vehicle.



Figure 2-2. Contractor-developed scanning rig including GPS, long-wave infrared, near infrared and LIDAR instrumentation.



### 2.1.3 Comparison to existing technology

This technology is similar to handheld infrared scanning technology in that both methods use infrared photographic methods. Unlike handheld methods which record still images, this process captures video infrared images. This method combines video data with GPS data, LIDAR data, and GIS data (e.g., building size, building age, envelope materials) to permit rapid data analysis, including quantification and prioritization of envelope energy leaks and an analysis of cost-effective methods of repair and improvement. Essess normally acquires GIS data from private companies. For military projects, GIS data are acquired from the installation being scanned (billing was provided). Because this is a video process, it is capable of scanning many buildings in a short period of time. Handheld infrared imaging methods would require many work-hours to achieve the same results.

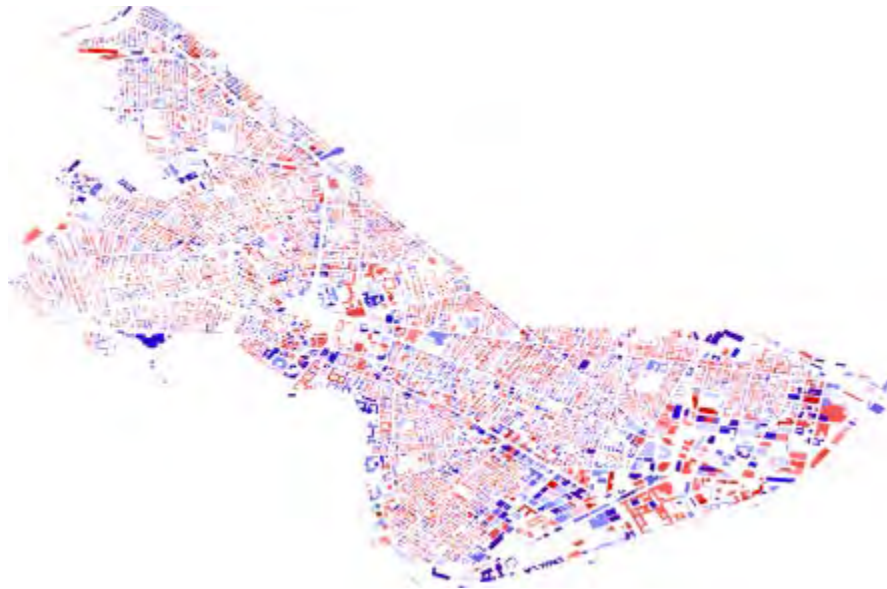
#### 2.1.3.1 *Future potential for USMC.*

This technology may prove to be a useful aid in operations and maintenance of facilities and in installation planning. Energy leaks identified using this technology can be analyzed and prioritized for the most effective use of O&M dollars. An installation's inefficient facilities can be identified and a cost associated with their condition can be used in prioritizing buildings for repair, major renovations or outright replacement.

#### 2.1.3.2 *Anecdotal Observations.*

The heat map of thermal imaging data collected from Cambridge, MA (Figure 2-3) shows a distribution of blue (efficient building envelopes) and red (inefficient building envelopes) buildings. In certain cases buildings of similar vintage, square footage, location, and style have very different envelopes in terms of energy efficiency. This suggests that there are numerous instances where thermal imaging data may very well be the main differentiating factor in determining building envelope quality between two otherwise similar structures even for cases where only one side of the building is visible from the street.

Figure 2-3. Building envelope efficiency map of over 17,000 buildings in Cambridge, MA.



#### 2.1.4 Energy analysis architecture

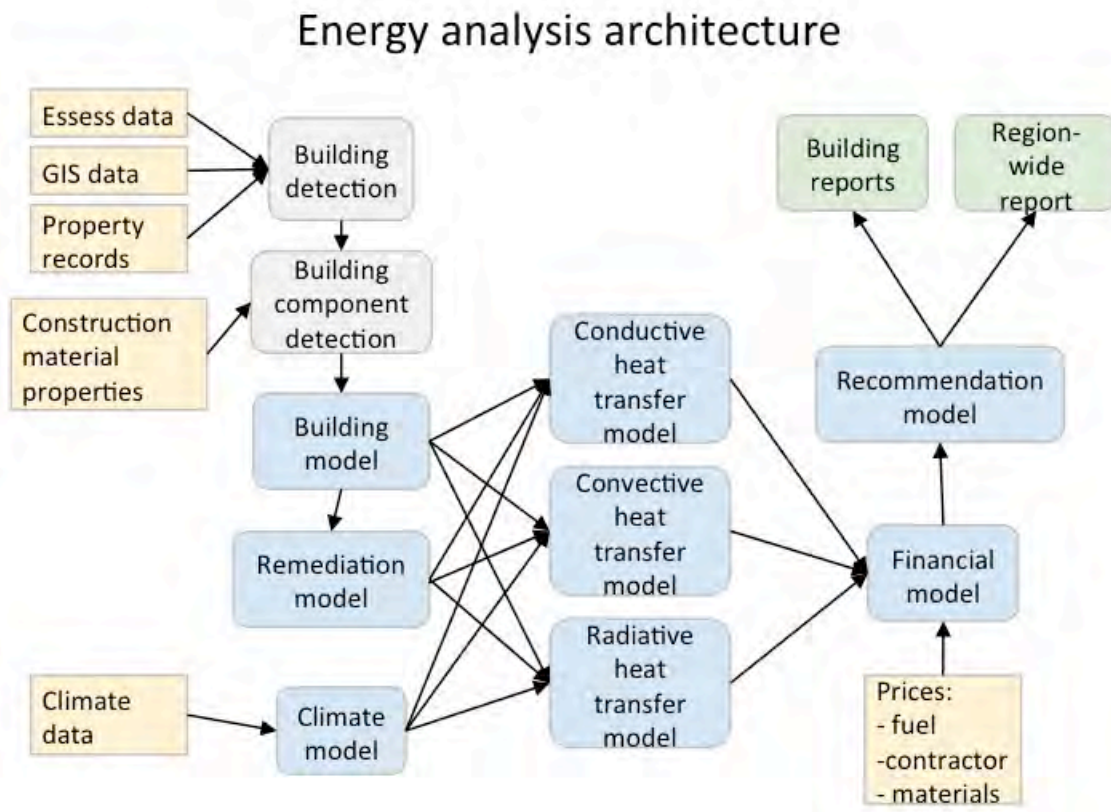
This “Essess Energy Analysis Architecture” is a unique hardware and software approach which develops very specific remediation recommendations to increase building energy efficiency. In the context of work in support of public utilities, it begins by combining scanning data with GIS data, public property records (for private sector residential buildings), and information on construction material properties, and produces building-specific energy reports and/or a region-wide energy analysis.

After the system scans a specific area, each scanned building is matched with its corresponding address or geographical location (latitude and longitude). Once a building has been detected and correlated to the correct address or building number, the construction material library, a database containing information on the emissivity of various types of materials, is used to differentiate, for example, a building’s window from a door. This phase is referred to as “building component detection.” It allows the algorithms to identify windows, doors, and other features of the building. Once a building and its building components are detected, those data are used to build a model to automatically detect similar buildings and similar building components in comparable datasets. These data are combined with a Remediation Model to automatically detect the building components that may need attention, and with a Climate Model to determine the weather-related variables of the scanning data. The Building Model, the Remedia-

tion Model, and the Climate Model are then used to develop a Conductive Heat Transfer Model to identify conductive leaks, a Convective Heat Transfer Model to identify convective heat loss, and a Radiative Heat Transfer Model to identify thermal radiation heat loss. The Conductive, Convective, and Radiative Models provide heat loss data that can then be combined with fuel prices, and labor and materials costs in the Financial Model. The Financial Model quantifies the energy loss and the potential dollars that can be saved by preventing the identified heat loss. Correlating the potential savings to specific fixes (Remediation Recommendation Model) allows the system to recommend the energy efficiency remediations that have the best ROI.

Figure 2-4 shows the Energy Analysis Architecture breakdown.

Figure 2-4. Schematic breakdown of the Essess Energy Analysis Architecture.



## **2.2 Technology development**

Essess is unique in the thermal imaging space as it is the only company in the world with the ability to scan thousands of buildings using a proprietary hardware device comprised of multiple sensors and a capability to process and analyze that data in a completely automated way. The hardware, which is comprised of the physical sensors on top of the vehicle, and the software which processes and analyzes the collected data are both based on research conducted at the Field Intelligence Lab at the MIT. Dr. Sanjay Sarma, Professor of Mechanical Engineering, recruited leading scientists and thought leaders to study the viability of remote, high-throughput thermal imaging at scale and develop techniques for identifying and assessing energy waste on a large scale.

The practical applications of high-throughput thermal imaging were researched and studied for multiple years before a prototype was built. The first imaging rig was tested in Cambridge, MA, and the data were analyzed to create a heat map overview of the city, as shown in Figure 2-3. The rapid scanning methodology and processing of imaging data were also demonstrated at Fort Drum, NY in February 2011.

After years of research and development and millions of dollars invested, Essess developed the current imaging rig which uses cutting edge technology to gather terabytes of data on a nightly basis. The custom hardware is augmented by advanced software algorithms that process the data. The system uses advanced machine learning and computer vision algorithms to scale up thermal imaging and processing to overcome the small-scale limitations of traditional infrared thermography which uses handheld cameras and requires manual analysis of each individual image.

## **2.3 Advantages and limitations of the technology**

### **2.3.1 Performance advantages**

This technology may improve energy efficiency by enabling USMC Civil Engineers to cost effectively scan and analyze most or all of the building envelopes on their installations to identify and prioritize the most significant energy leaks and to implement measures that repair or improve existing building envelopes or identify and prioritize buildings that warrant major renovations or outright replacement. With handheld thermography

methods, it would be too costly and time consuming to perform infrared scans and analyze the data for large numbers of buildings.

### **2.3.2 Cost advantages**

For large sets of buildings, this technology should be much more cost-effective than traditional handheld methods of performing infrared thermography scanning and analysis of buildings. Handheld IR scanning methods are much more time consuming, resulting in significant added labor costs.

### **2.3.3 Performance limitations**

This technology is limited to scanning the street sides of buildings. As a result, for most buildings, four sides of the buildings will not be scanned. Two or three sides are typically scanned depending on the orientation of a building relative to the street. This technology is also limited by the requirement to have a minimum  $\Delta T$  between building interior and exterior ambient temperatures of at least 20 °F, so scanning must occur when nighttime temperatures are below 50 °F. This limits application of this technology to regions where there is at least 1 week of the year in which nighttime temperatures are below 50 °F. Most regions of the United States fall within this boundary condition. Adjustments are made for empty buildings or buildings where there is no internal heating and no way of knowing the internal temperature setpoint (discussed in Section 4.3.3). This technology is somewhat hindered by trees, bushes and other obstructions that might partially obscure a clear view of a building's envelope from the street. However, the automated data processing pipeline developed by Essess to take the scanned data and prepare it for a report format corrects for these kinds of obstructions in a number of ways that have been tested by Essess.

### **2.3.4 Cost limitations**

There is a lower limit of the number of buildings that can be cost effectively scanned and analyzed by this method. Below this limit, it is more cost-effective to identify and analyze building envelope energy leaks by another method. This demonstration sought to determine this cutoff point. As referenced in Table 1, *Performance Objectives*, the average cost for performing a handheld thermal audit on a 5,000 sq ft commercial building is ap-



proximately \$1000 (or \$0.20 per sq ft). Considering Essess charges approximately \$200,000 per installation, it would be beneficial to perform an Essess scan for any installation that has at least 1 million sq ft in buildings (determined by adding the individual square footage of each building scanned). For perspective, over 4.2 million sq ft of buildings were scanned at Camp Lejeune.

It was also considered desirable to document the cost structure of this technology to help USMC Civil Engineers determine how the technology might fit within the constraints of their business process. For example, this technology is able to capture scan data on hundreds or thousands of buildings in a very short period of time such that very large installations could be scanned within a matter of days. The resulting marginal cost of scanning buildings is relatively inexpensive. However, the process of analyzing scan data to identify and prioritize energy leaks is more challenging and has a significantly higher marginal cost. Since both of these processes must be done together to provide a military installation with actionable results, documenting the cost structure for these services will help Facilities Engineer determine how they might benefit from Essess thermal imaging.

### **2.3.5 Social acceptance**

There were no problems associated with social acceptance by installation staff. This technology had little or no impact on the activities or processes of the installations. On-site activities were conducted at night when very few installation operations were occurring. The only burden placed on installation personnel was the need for them to provide installation GIS data and energy data for analysis requirements. The GIS data were a necessary component of the scanning process as they allowed Essess to correlate the scanned image of a building with the building's exact geographical location. The energy data allowed Essess to calibrate the results of the thermal envelope analysis.

Table 2-1. Summary of performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria		Results
			Quantitative Performance Objectives		
Rapid scanning	Buildings scanned per hour	Number of Buildings scanned and required time	> 100 Buildings per hour		<i>Camp Lejeune:</i> <ul style="list-style-type: none"><li>• Approx. 110 buildings per hour scanned.</li><li>• 1,307 buildings and other objects (e.g., sheds, lamps, and other unheated structures) were scanned. Total imaging time was 11hr54min after adjusting for various delays including inclement weather.</li></ul>
Rapid analysis	Buildings per hour	Number of Buildings analyzed and required time	> 50 Buildings per hour		Approx. 327 buildings per hour for both Scott Air Force Base (AFB) and Camp Lejeune (leaks identified as polygons and subsequently analyzed)
Actionable results	Building envelopes determined to be adequate (needing no improvements) or improvement projects scoped for envelopes having identified deficiencies	Number of envelopes deemed adequate and/or having projects scoped to correct identified deficiencies	For each installation, the envelopes of at least 25 of the 30 buildings selected for detailed analysis are deemed to be adequate or have projects identified to correct deficiencies		<i>Camp Lejeune:</i> <ul style="list-style-type: none"><li>• 1,037 - Window Frames</li><li>• 201 - Door Frames</li><li>• 412 - Walls</li><li>• 232 - Roofs</li><li>• 329- Soffits</li></ul> See Chapter 5(Performance Assessment) for more detail
Cost effectiveness	Cost (\$) for square footage of building scanned and analyzed/report ed.	Scanning, analysis and reporting costs for various numbers of Bldgs, similar costs for handheld methods	Cost below handheld methods for scanning 1million sq ft of building space or more, Simple payback = 10 years. (Since buildings can vary from a few hundred to several thousand square feet, total building square feet was used as a metric to measure the cost effectiveness of handheld versus mobile thermal imaging)		<i>Camp Lejeune:</i> Handheld thermography audits would have cost an estimated \$840,000 based on 4.2 million sq ft scanned. Esess costs for Camp Lejeune were approx. \$200,000

Performance Objective	Metric	Data Requirements	Success Criteria		Results
Qualitative Performance Objectives					
Robust technique within defined range of operating conditions	High quality scanned imagery	Scan data quality under a range of environmental operating conditions	"High Confidence***" in results obtained within defined limits	Success: Within the defined range of operating conditions, the Thermal Imaging System is capable of capturing high quality data that can be analyzed for envelope issues.	
Comparing the Fidelity and Usefulness of Imagery at Varying Scanning Distances	Measuring the image quality of data taken at varying distances starting at 20 yds and ending at 180 yds with 20 yd intervals	Thermal images taken by mobile imaging rig at 20 yd intervals from 20 to 180 yds	"High Confidence****" that the temperature data can be seen at extreme distances	The results show that infrared imaging is capable of capturing temperature data at 180 yds. However, the number of pixels in the frame limits the data quality.	
Street-side scanning sufficient	Representativeness of street-side sample vs. 360-degree scan of building using handheld methods	Street-side drive-by scan results 360-degree handheld scan results	"High Confidence****" that results of street-side scans adequate for planning purposes	Street-side data is representative of sides not seen from the street	
Ability to usefully scan Bldgs obscured by wall of trees and other obstructions	Data loss due to obstructions	Leaks obscured by obstructions	"High Confidence" that obstructions do not appreciably impact results	Line-of-sight between imaging system and building is required for data capture. The imaging rig is able to capture data when driving by a single tree or utility pole, but is unable to capture data when the building is completely blocked from the imaging rig (i.e., with a fence, multiple trees, etc.). This was previously tested while the technology was in research and development.	
* Commercial energy audits that include envelope thermal imaging using handheld thermography can typically cost around \$1,000 for a 5,000 sq ft. building and \$10,000 for a 50,000 sq ft. building (based on data from thermal imaging auditors within 100 miles of Scott AFB and Green-Buildings.com). At Camp Lejeune, Essess imaged 4.2 million sq ft and 147 buildings. Unlike a typical auditor that charges per building, Essess' cost structure is on a per installation basis. This is due to the fact that the bulk of Essess' costs are front-loaded. Once the imaging rig is deployed to an area, there is only a marginal cost in imaging 1,000 buildings versus 100 buildings.					
** "High Confidence" is a visual examination by an Essess scientist resulting in a determination that the data can be used for performing an analysis of the building envelope.					

## **3 Facility/Site Description**

### **3.1 Facility/site selection criteria**

#### **3.1.1 Geographic criteria**

The mobile scanning technology is relevant to climate zones where the heating season  $\Delta T$  (indoor to outdoor temperature) can be expected to be at least 20 °F during the building scanning period. As a result, this technology may not be applicable to certain regions within Climate Zones 1 and 2. This demonstration selected installations in Climate Zones 3, and 4, with the potential for Zone 5. Also, installations were chosen that had a large number of significant buildings from which to select. The technology is also capable of capturing data during cooling season as long as the  $\Delta T$  (indoor to outdoor temperature) is 20 °F.

#### **3.1.2 Facility criteria**

This demonstration worked with the installations to select buildings typical of modern installations. Buildings selected included command headquarters, dormitories, training facilities, admin facilities and similar large buildings. At each installation, a minimum of 250 buildings were scanned and a detailed analysis of 30 buildings, selected by the installation, was performed.

#### **3.1.3 Facility representativeness**

The installations selected are very large and had a full range of facility types and buildings of various vintages. The buildings and building types at the selected installations were quite representative of buildings that would be found at other military installations.

### **3.2 Facility/site location and operations**

#### **3.2.1 Demonstration Site #2: Camp Lejeune, NC**

Camp Lejeune is a 246-sq-mi U.S. Marine Corps training facility located along the Atlantic Coast in Jacksonville, NC (Figure 3-1). The main base is supplemented by five satellite facilities: Marine Corps Air Station New River, Camp Geiger, Stone Bay, Courthouse Bay, Camp Johnson, and the latest addition to the facility, the Greater Sandy Run Training Area.

Camp Lejeune is the largest Marine base on the East Coast. The base's 14 miles (23 km) of beaches make it a major area for amphibious assault training, and its location between two deep-water ports (Wilmington and Morehead City) allows for fast deployments. Since the on-site activities associated with this demonstration were very short term, there was little or no interaction between this project and normal military activities.

Figure 3-1. Location of Camp Lejeune, NC.



## **4 Test Design**

### **4.1 Conceptual test design**

#### **4.1.1 Hypothesis**

Compared to using traditional handheld thermography, the demonstrated drive-by thermal imaging technology gathers energy efficiency information from the building stock in a manner that is faster, more cost-effective, and easier to scale.

#### **4.1.2 Independent variable**

The main independent variable being tested was the KSR LWIR imaging and analysis process.

#### **4.1.3 Dependent variable(s)**

Dependent variables measured included emissivity, building type, building square footage, and scene occlusion. Other variables tested during the demonstration process included:

- Scanning time (scanning time using a mobile imaging system versus scanning time using a handheld thermal camera to determine scalability in terms of time)
- The effects of resolution when scanning with the imaging rig versus scanning with a handheld camera to determine importance of image quality
- Scanned image quality from varying distances (specifically 20 meters, 50 meters, and 100 meters).

#### **4.1.4 Controlled variable(s)**

Controlled variables included the pre-selection of building types of similar size and building materials for scanning and analysis by both the drive-by and the handheld methods. Both scanning methods were conducted simultaneously to ensure identical temperatures and weather conditions during scanning operations.

#### **4.1.5 Test design**

The demonstration of the long-wave infrared (LWIR) imaging technology took place during February and March 2014. Multiple buildings were scanned at Camp Lejeune, NC using the thermal imaging rig. Six buildings were scanned at the installation using both the drive-by scanning rig and a traditional handheld thermal camera to set up the comparative analysis between the two methods of thermal data gathering. Note that the conventional handheld analysis was carried out under the same weather and temperature conditions as the mobile imaging scan to ensure that the data being captured was comparable. All attempts were made to tightly monitor the controlled variables for both the imaging rig and the handheld scans. The scanning process began 2 hours after sunset and concluded 30 minutes before sunrise on nights with temperatures below 50 °F. The imaging rig captured and recorded data on hard drives that were mailed back to Essess headquarters for processing. Images were analyzed with respect to energy loss via infiltration, damaged building components, inadequate insulation, and thermal bridges. The imaging data was combined with GIS information, LIDAR data, and other building data. Note that thermal images taken with a handheld camera were not processed by automated methods, but were (necessarily) visually analyzed by a human auditor, which makes the process less efficient and more difficult to scale.

#### **4.1.6 Test phases**

##### *4.1.6.1 Phase 1*

Tests were done to determine whether the mobile LWIR imaging could collect building envelope efficiency data faster than traditional handheld thermography without compromising the quality of the diagnostic data by customizing the imaging rig specifically for gathering data on a military installation. For example, a distortion map was created for NIR cameras, the NIR illuminator was adjusted for imaging buildings further back from the street than typical residential homes, the sweeping LIDAR was configured to compensate for poor street information, and the onboard GPS units were configured for optimal imaging in areas with low satellite access. The viewing angle for the entire hardware device was adjusted to optimally capture buildings larger than a typical residential home. A custom logistics dashboard was also created and tested to allow the logistics team to efficiently validate data being captured across the military base. The validation is important as it allows the driving team operating the vehicle to

see the data being captured through the onboard monitor. A handheld thermal imaging camera was also used. The LWIR cameras converted camera output data from pixel values to temperatures. Other subtasks included optimizing imaging hardware based on potential building materials to be encountered on military installations; finalizing the logistics plan for the Imaging Team, coordinating base access and finalizing paperwork for clearance; and training Data Collection Technicians on using the onboard logistics dashboard.

#### 4.1.6.2 Phase 2

The contractor drove to the specific military installations and scanned the installations using the imaging vehicle, and captured data using the handheld camera for a subset of the buildings scanned by the imaging vehicle. The contractor set up comparative tests to determine the quality of data collected from the mobile imaging process relative to the data collected from the conventional thermal imaging method. For example, a data quality test was conducted to determine the difference between gathering the street-view of a building versus capturing all sides with a manual camera. The captured data were verified through manual curation, and The contractor worked with on-base facilities managers at each base to access GIS and energy information. The contractor customized an analysis pipeline for post estimation and converting raw images to temperature images and data processing. The data were processed to match images to both vehicle GPS data and GPS data gathered from the military installations. After this, the captured data were correlated to building information obtained from the military installations. Further analysis was focused on building materials and correlated thermal inefficiencies to the areas imaged. The processing pipeline was configured to calculate energy scores for scanned buildings and determine the least efficient buildings. The results were published through an automated system that could be visualized using a front-end tool to manually verify building issues.

#### 4.1.6.3 Phase 3

The contractor used the Drive-by Visualization Application to identify buildings that required further analysis and also provided the application to the installations to downselect a subset of 30 buildings for detailed analysis. The Drive-by Visualization Application was an online platform that displayed the thermal imaging video, a map of the base, and a list of the buildings selected for further analysis. The user then selected or unselected a par-



ticular building for analysis. The gathered data from the handheld scanner were analyzed to provide a detailed comparative analysis.

#### **4.1.7 Fundamental problem**

Collecting useful building envelope energy efficiency data using traditional auditing methods is slow, costly, and difficult to scale. The demonstrated technology creates a new way to collect and analyze building envelope energy efficiency data, and augments (and in certain cases completely replaces) manual handheld audits of the building's envelope.

#### **4.1.8 Demonstration question**

Can mobile thermal imaging collect building envelope energy efficiency data faster and more cost effectively than traditional handheld thermography without compromising the quality of diagnostic information being acquired?

### **4.2 Baseline characterization**

#### **4.2.1 Reference conditions**

The following data were collected for Camp Lejeune: building footprints (in the form of GIS polygons), parcel footprints (in the form of GIS polygons), address points, address metadata, energy consumption data (gas and electrical, only available for certain buildings) for multiple years for each metered building, building vintage (only partially available buildings), and building size (only partially available).

Data collected by the imaging rig on scanning nights included: ambient temperature, ground temperature, sky temperature, and precipitation levels

Camp Lejeune was able to provide GIS data. Energy data were not available for all buildings scanned.

#### **4.2.2 Baseline collection period**

The data for Camp Lejeune were collected over the period of 10-14 February 2014. Data were collected on nights where the temperature and weather conditions were conducive to thermal imaging. Handheld thermography images were captured on the same nights.

### **4.2.3 Existing baseline data**

Given the nature of the technology and this demonstration, there was no baseline data for comparison purposes.

### **4.2.4 Baseline estimation**

The cost of conventional handheld infrared thermography was estimated based on the cost of equipment and the market rate of skilled labor to perform the analysis. Measurements of selected buildings were taken with handheld infrared cameras to create a baseline to compare with the results from the vehicle-mounted rig.

## **4.3 Design and layout of system components**

### **4.3.1 System design**

The thermal imaging rig combines several commercial off-the-shelf (COTS) sensors with custom electronics, software and environmental housing to record data samples:

- Trimble A3000 DR+GPS
- Velodyne HDL-32e 3D LIDAR
- (4) FLIR A65 Thermal imaging cameras
- (2) Allied Vision Technologies Manta G-283B Camera
- SICK LMS111-10100 2D LIDAR.

The Trimble GPS along with the front facing SICK LIDAR were used to continuously estimate the position of the car during the scanning process. The Velodyne LIDAR was used for 3-D reconstruction of buildings and other structures. The Manta cameras were used with the computer vision system to detect near infrared features. Thermal measurements were made with the FLIR long-wave infrared cameras. The data produced by these systems were recorded to a mirrored set of hard drives, and were post-processed using computer vision, machine learning, and thermal analysis algorithms to generate actionable envelope intelligence.

### **4.3.2 System layout**

Figure 4-1 shows the multi-sensor imaging hardware. The GPS antenna maps the location of the car, the LIDAR creates a dense pointcloud to determine the 3-D landscape, the long-wave infrared (LWIR) cameras measure heat, the near infrared (NIR) cameras are able to detect building fea-

tures similar to what someone might see through a night vision camera, and the NIR illuminator acts as a floodlight for the NIR camera.

Figure 4-2 shows a schematic outline of the proprietary Thermal Imaging System.

Figure 4-3 shows a snapshot of the user interface for the onboard data capture and diagnostic system interface that allows an imaging technician to validate the data as they are collected.

Figure 4-1. Essess' multi-sensor imaging hardware.

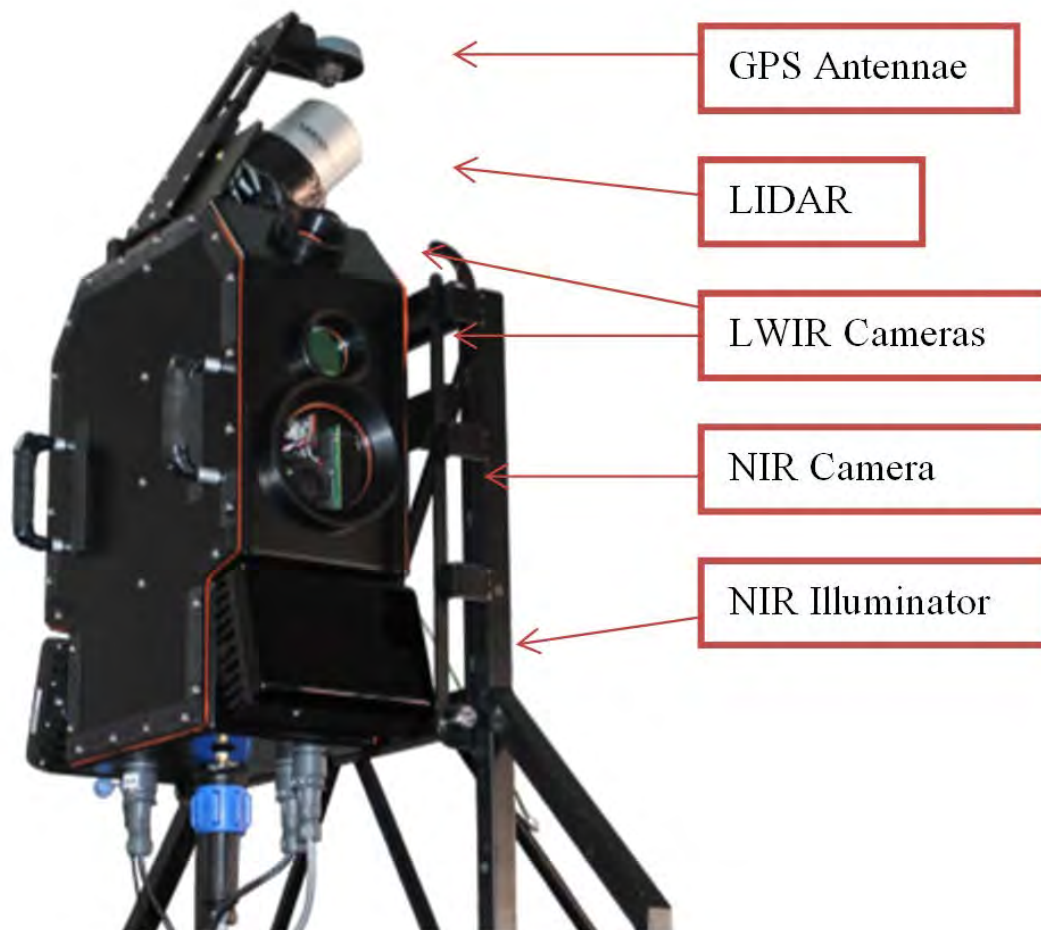


Figure 4-2. Schematic outline of the proprietary Essess Thermal Imaging System.

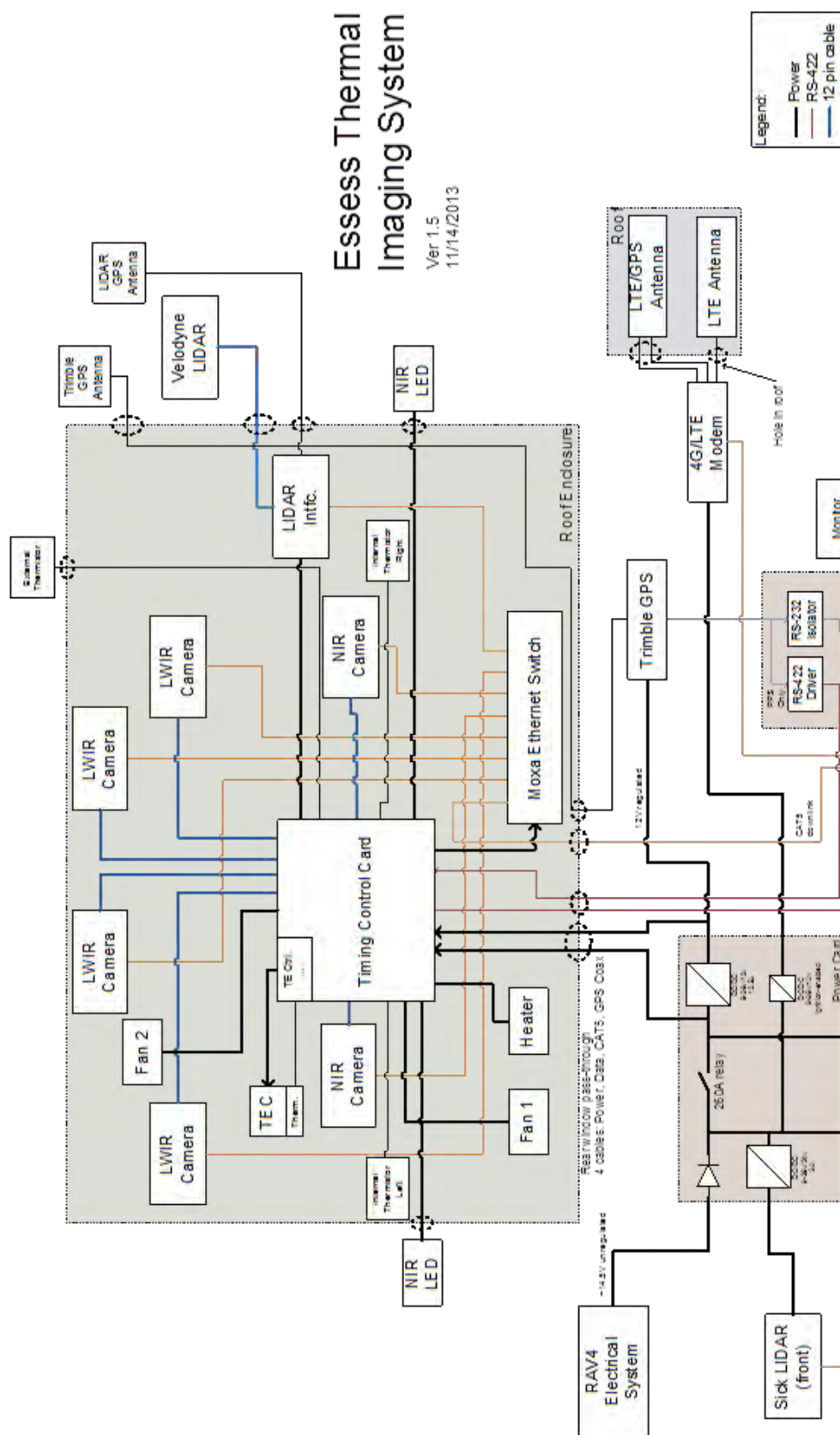


Figure 4-3. User interface for the onboard data capture and diagnostic system.

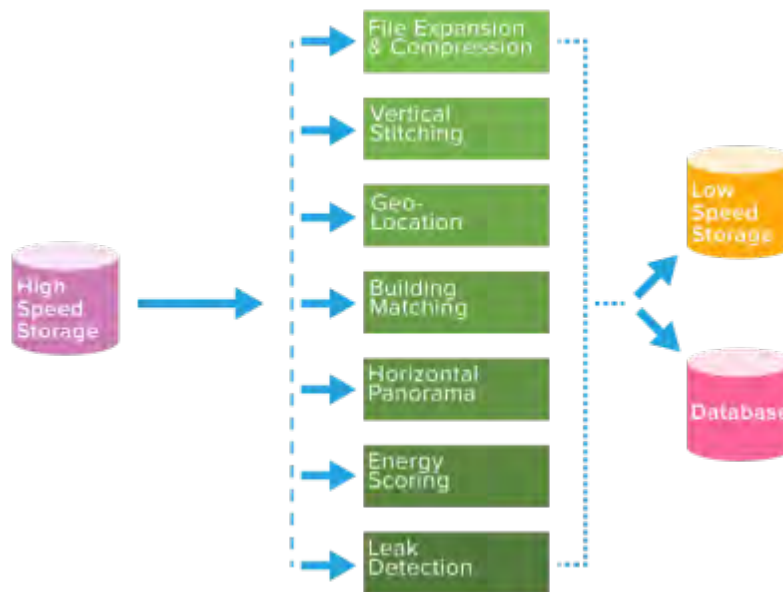


Figure 4-4 shows a very general overview of some of the key steps in the data processing pipeline, including:

- *High Speed Storage.* Each imaging vehicle captures several terabytes of data per night, which are stored in the Customized Vehicle Data Storage System.
- *File Expansion and Compression.* The compressed data are extracted from the hard drives to begin processing and analysis.
- *Vertical Stitching.* The vehicle is equipped with two LWIR cameras on each side of the imaging device and each camera captures a part of the scene as the vehicle passes by. To get a robust, vertical image of the scene, data streams from the two cameras are stitched together using proprietary algorithms.
- *Geo-location.* All of the data from the GPS units are analyzed and then combined with LIDAR information to adjust for any external noise or loss of satellite signal.

- *Building Matching.* Once the GPS data are processed and analyzed, they are matched up with the relevant thermal images for each building imaged.
- *Horizontal Panorama.* As the data are captured frame by frame, there may be tens or hundreds of individual images, each showing a small part of the entire scene. To get a seamless panorama of an entire building, the frames must be stitched together.

Figure 4-4. General overview of the Essess data processing pipeline.



- *Energy Scoring.* Once the images are extracted, vertically stitched, correlated with the relevant address, and horizontally grouped, they are analyzed to convert the thermal reading into an energy score. This energy score is relevant to each data set and allows for one building to be compared to a different building within the same data set.
- *Leak Detection.* The images are also analyzed for potential building envelope leaks.
- *Low Speed Storage.* All of the raw data are then placed in low speed storage.
- *Database.* The analyzed and processed data are stored in a database. Customers can then access this data using web applications layered on top of the database.

### 4.3.3 Heat flux calculation methodology

#### 4.3.3.1 Calculating heat flux

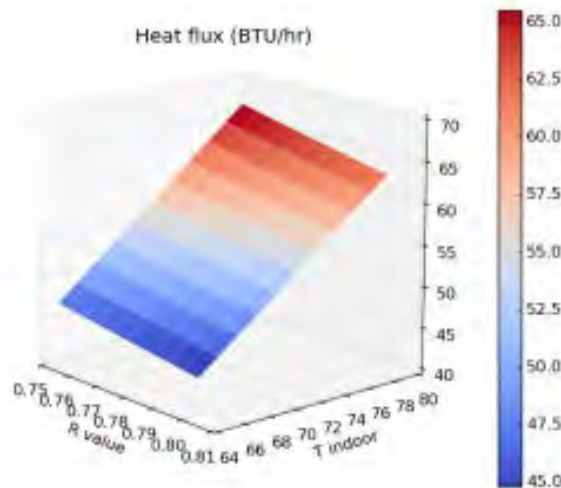
Heating energy losses (Figure 4-5) due to conduction through walls, roofs, windows, doors, and soffits were calculated by the equation:<sup>[1]</sup>

$$Q_{h,d} = A \cdot U \cdot (T_{in} - T_{out}) \quad (4-1)$$

where:

$Q_{h,d}$	=	Total hourly rate of heat loss through surface in Btu/hr
$U$	=	Overall heat transfer coefficient of surface in Btu/hr-ft <sup>2</sup> -°F
$A$	=	Net area of surface in ft <sup>2</sup>
$T_{in}$	=	Inside temperature in °F
$T_{out}$	=	Outside temperature in °F.

Figure 4-5. Heat flux (Btu/hr).



This analysis focused only on heat loss and assumed an indoor average thermostat ( $T_{in}$ ) setting of 69 °F ± 4 °F (65 °F to 73 °F). This is slightly lower than the actual most likely thermostat setting to account for internal heat gain due to lighting, electronics, and machinery.

The hourly outdoor temperature ( $T_{out}$ ) was obtained from the National Climate Data Center (NCDC) Quality Controlled Local Climatological Database (QCLCD).

The area of the surface was determined based on the relative size of polygons drawn on the building compared to door polygons (or synthetic door

polygons when doors are not present). Doors were assumed to have an area of 20 sq ft, and were drawn individually so as not to conflate double doors with single doors.

The U value of elements of the building envelope were estimated based on their surface material, brightness, and the relationship between the indoor temperature, the surface temperature, and the outside air temperature. Specifically, calculations were done to determine the heat loss (radiative + conductive to the outdoor ambient air) of a material to the outside air assuming steady state for that heat flux and the estimated indoor temperature, then to determine the R value for that portion of the building surface. The approach taken is described in detail in the subsequent section.

The sensible heat loss from infiltration can be calculated as [2]:

$$Q_{h,i} = V_{cfm} \cdot \rho_{air} \cdot C_p \cdot (T_{in} - T_{out}) \cdot 60 \quad (4-2)$$

where:

$Q_{h,i}$	=	sensible heating load from infiltration in Btu/hr
$V_{cfm}$	=	volumetric air flow rate in cubic feet per minute (CFM)
$\rho_{air}$	=	the density of the air in lb/ft <sup>3</sup>
$C_p$	=	specific heat capacity of air at constant pressure in Btu/lb°F.

The indoor and outdoor temperatures are the same as above. The density of air ( $\rho_{air}$ ) is, on average, 0.074887 lb/ft<sup>3</sup>. The specific heat capacity of air ( $C_p$ ) is assumed to be 0.2403 Btu per (°F) (lbs).

The volumetric air flow rate per linear foot of door and window frame cracks was assumed to be 0.52 CFM on average for a pressure differential of 75 Pascals, with a standard deviation of 0.4 CFM and a minimum of 0.01 [3, 4, 5, 6]. At an average interior to exterior pressure differential of 10 Pascals, this translates into a mean CFM of 0.14, based on the functional relationship between air flow and pressure [3]:

$$Q = C(\Delta P)^{0.65} \quad (4-3)$$

The volumetric air flow rate of any given foot of leaks was estimated based on its relative emissivity compared to the mean of all observed windows and doors with the assumption that the distribution of leaks at both bases roughly matches that found in the literature [3,4,5]. Windows and door-frames were tagged separately from the window glass or door material, and the linear feet of cracks were estimated based on the dimensions of the



frame relative to the door reference described previously. The mean emissive cracks were assigned an estimated value of 0.14 CFM; the 95<sup>th</sup> percentile of emissive cracks was assigned an estimated value of 0.36 CFM.

Total heating losses can be calculated as the sum of conductive and convective heating losses, adjusted based on the efficiency of the heating equipment. Assuming a natural gas space heating system with an average fuel use efficiency ( $f_{afue}$ ) of 70% per the Illinois Technical Reference User Manual (TRM) default assumption for existing systems in commercial buildings [6], total heating losses (in therms per hour) were calculated as:

$$H_{therms} = \frac{Q_{h,d} + Q_{h,i}}{f_{afue}} \cdot \frac{1}{99,976} \quad (4-4)$$

Total cooling losses were estimated as the sum of conductive and convective cooling losses, with a typical Seasonal Energy Efficiency Ratio (SEER) of 10 Btu/watt-hour ( $f_{seer}$ ) per the typical value of existing equipment in the TRM [6]:

$$C_{kwh} = \frac{Q_{c,d} + Q_{c,i}}{f_{seer}} \cdot \frac{1}{3,412} \quad (4-5)$$

Figure 4-6 shows an example of the results of this approach for a characteristic brick wall. For the time being, energy losses due to latent heat were excluded from this analysis. The analysis assumes a cost per kWh of \$0.056 and cost per therm of \$0.59.

Figure 4-6. Brick wall cost.



#### 4.3.3.2 Inferring $R$ -values

$R$ -values were inferred by using a conservation of energy principle to assume that all energy leaving the surface of the material is matched by the energy flowing through the material. If the system is at steady state, the heat flowing through the material is equal to the heat leaving the material surface:

$$q_{through} = q_{exit} \quad (4-6)$$

Where  $q_{through}$  is the heat flux through the material (inside the building to outside) and  $q_{exit}$  is the heat flux leaving the material and escaping into the atmosphere. The leaving heat flux can be split into two components: radiation (beaming photons) and conduction (warming up the film of outside air that touches the material).

$$q_{exit} = q_{rad} + q_{cond} \quad (4-7)$$

The radiation heat flux is:

$$q_{rad} = \epsilon \sigma A (T_{surf}^4 - T_{out}^4) \quad (4-8)$$

where epsilon ( $\epsilon$ ) is the emissivity of the gray body (a description of how shiny the material is), sigma ( $\sigma$ ) is the Stefan-Boltzmann constant, area ( $A$ ) is the material surface area, surface temp ( $T_{surf}$ ) is the material's external surface temperature, and outdoor temp ( $T_{out}$ ) is the ambient outdoor air temperature. Here it was assumed that most objects that are radiating back toward the building material were at approximately the ambient air temperature.

The exiting conductive heat flow is:

$$q_{cond} = hA(T_{surf} - T_{out}) \quad (4-9)$$

where  $h$  is the heat transfer coefficient of air.

This exiting heat flux is equal to the heat flux through the material:

$$q_{through} = \frac{(T_{in} - T_{out})A}{R} \quad (4-10)$$

where  $R$  is the thermal resistance and indoor temp is the indoor air temperature.

Solving for the thermal resistance:

$$\hat{R} = \frac{A(T_{in}-T_{out})}{q_{through}} = \frac{A(T_{in}-T_{out})}{q_{exit}} \quad (4-11)$$

As mentioned previously, this method only produces an unbiased estimate of R-values in cases where the system is at a steady state. In practice, this will often not be the case due to residual solar heating of material surfaces and uncertainties in precision of measured surface temperatures and outdoor air temperatures. Failing to account for these will tend to result in a systemic underestimate of R-values, and concomitant overestimate of remediation potentials.

To effectively control for these uncertainties, the resulting R value estimates were normalized based on a prior distribution of assumed R-values in the literature [7, 8] for each component (Table 4-1).

Table 4-1. Current component R-values and new component R-values

Component Name	Current Component R-Values				New Component R-Values			
	Min	Max	Mean	St Dev	Min	Max	Mean	St Dev
Window – Glass	0.99	2.99	1.69	0.25	0.99	2.99	1.69	0.25
Door – Wood	1.85	3.7	2.17	0.5	1.85	3.7	2.17	0.5
Door – Metal	6	15	10	2.5	6	15	10	2.5
Door – Glass	1.8	5	2.5	0.5	1.8	5	2.5	0.5
Soffit	8	16	12	3	8	18	14	3
Exposed Foundation	6	14	10	2	6	14	10	2
Wall – Brick	8	16	12	3	8	18	14	3
Wall – Stone	6	12	8	2	6	14	10	2
Wall – Siding	6	12	8	2	6	14	10	2
Wall – Concrete	6	12	8	2	6	14	10	2
Roof	10	20	14	3	10	20	15	2.5
Wall – Thermal Bridge	4	12	8	2	8	18	14	3

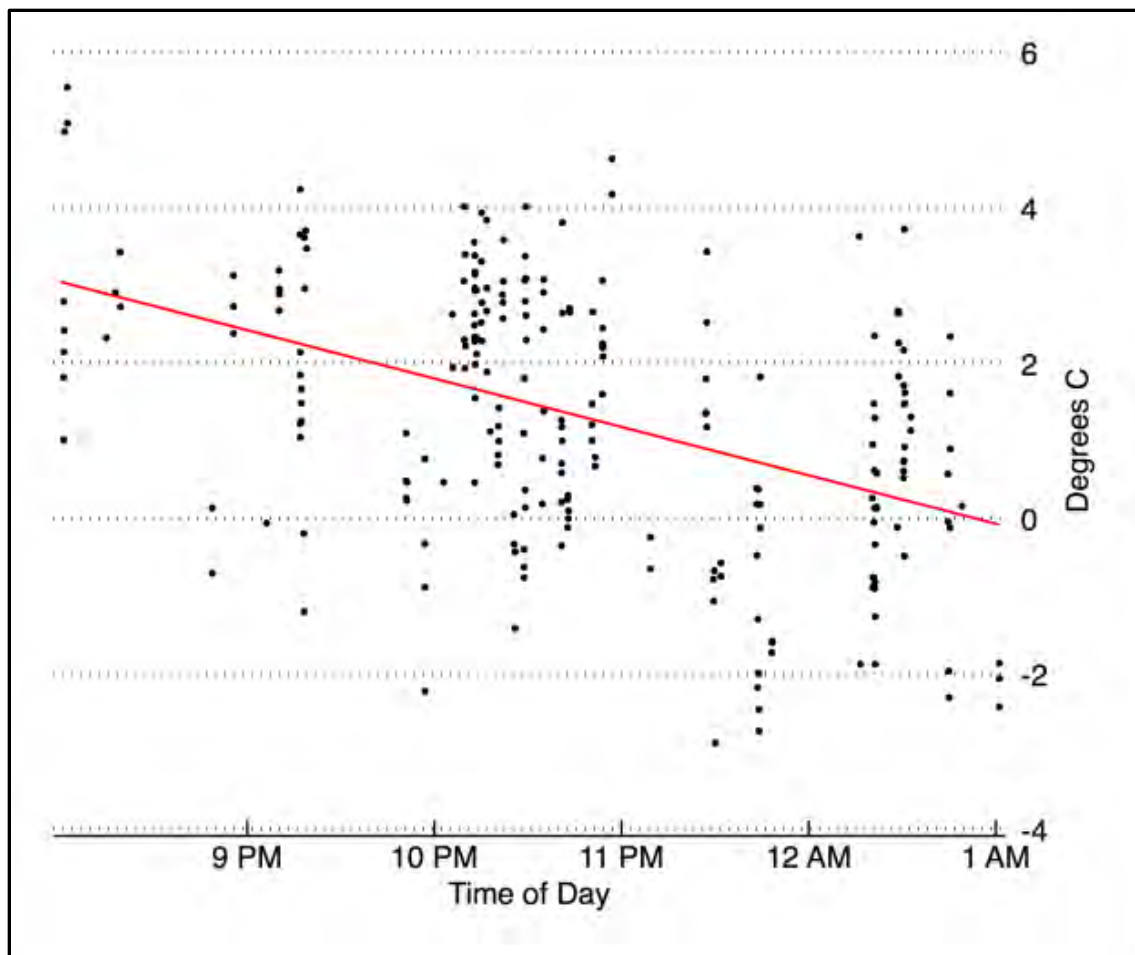
Specifically, it was assumed that individual identified components on the base map to a distribution of current component R-values, such that the 10<sup>th</sup> percentile of brick walls on the base, would fit the 10<sup>th</sup> percentile of the normal distribution of current component brick wall R-values in the table.

This approach was conducted separately for areas with and without significant sunlight exposure on the evening of 28 February 28 2014 (e.g., south and southwest-facing surfaces between 120 and 300 degrees) [9]. This

should help control for bias due to residual solar heating, as all surfaces observed around the same time with the same orientation will have similar biases. The relatively early cessation of direct sunlight also helps, as sunset occurred at 15:52.

An additional analysis was done to measure the effect of the imaging time on the surface temperature of buildings. Figure 4-7 shows the results for south-facing brick walls, which broadly indicate most other components observed. Given that the effect of time of observation on resulting surface temperatures is roughly equal in magnitude to the variation in surface temperature among buildings sampled, an explicit time-of-observation correction was warranted, using a simple ordinary least squares de-trending approach on each combination of building component and orientation to normalize for time of observation.

Figure 4-7. Building surface temperature values over time.



Additional factors that may introduce bias into the estimate included:

- *Unknown Material Types.* Currently, the process relies on human curators to tag the building component with the correct material type. If this type is wrong, then the model is no longer as accurate. This could be addressed by additional validation of component material types against aerial imaging, as well as review by base staff.
- *Imprecise Local Temperature.* Currently, ambient outdoor air temperatures are read from weather station logs, which are precise only to a single degree Fahrenheit. This introduces some error in the heat flow model, which is sensitive to temperature values. This could be addressed by incorporating data from the vehicle-mounted temperature sensor, or by readings from an on-base weather station.
- *Unknown Indoor Temperature.* Because it is impossible to read indoor temperature through the building surface, it must be estimated. In this work, indoor temperature was estimated using common temperature values that most people find comfortable, such as 65-73 °F in the winter and 70-78 °F in the summer. This could be addressed by receiving more information from facility managers regarding indoor summer and winter thermostat setpoints.
- *Uncertain Space Heating and Cooling Efficiencies.* There is a range of potential efficiencies of 60–95% for space heating and SEER ratings of 8 to 18. Lack of detailed information about building-specific heating, ventilating, and air-conditioning (HVAC) equipment prevented these estimates from being further refined. Currently, mean estimates, of 85% AFUE for Lejeune, were used (as the upcoming replacement of the central steam plant will entail new space heating equipment installations). A cooling system SEER of 10 was used for both bases.

#### 4.3.3.3 *Temperature data analysis*

To determine the potential savings of remediation measures over the cooling and heating seasons, assumed indoor temperatures were compared to typical outdoor temperatures based on average hourly data over the past 5 years from the National Weather Service via the NCDC's QCLCD [10]. Missing values were in-filled by adding an interpolated anomaly field to the average climatology of the missing hourly reading.

#### 4.3.4 **System integration**

Although both handheld thermography and mobile thermal imaging use LWIR to determine energy loss, the imaging rig supplemented LWIR with

NIR, LIDAR, GPS, and other sensors to gather better building diagnostic data. As a result, the final analysis can fully replace traditional handheld methods for gathering external building envelope data. This mobile thermal imaging technology allows the military to conduct baseline building envelope energy efficiency audits for hundreds of buildings in a matter of hours instead of months.

## 4.4 Operational testing

#### 4.4.1 Operational testing of cost and performance

Data collection involved having an imaging rig drive to a given location and scan the area based on pre-defined, routing tracks. The Imaging Team waited until sunset to set up the system and then to begin imaging. This mitigated the effects of solar radiation and allowed the team to capture data at a period with the largest temperature difference (middle of the night). To ensure that the best data were captured, the contractor avoided imaging during any kind of precipitation events. Costs captured for driving the imaging rig included technician labor costs, cost of fuel for the imaging rig, and operating and maintenance costs.

#### 4.4.1.1 Modeling and simulation

All imaging data were logged onto the onboard data capture and diagnostics system. The onboard imaging technician was able to view the data as they were recorded to spot any problems in the data quality. Once the data were sent to Essess headquarters, they were processed and used for algorithmic testing. The algorithmic testing provided information on the cost, time, and image quality for mobile imaging versus traditional handheld thermography methods.

#### 4.4.1.2 Timeline

Operational testing plan (Table 4-2) commenced in February 2014.

**Table 4-2. Essess schedule of work.**

[illegible]

#### 4.4.1.3 Decommissioning

There was no need for decommissioning since this project involves a contracted service and a mobile scanning system.

#### 4.4.2 Equipment calibration and data quality issues

The field engineer used an asymmetric circle calibration grid to optically calibrate the long-wave infrared cameras according to industry best practices (Figure 4-8) The thermal calibration was conducted using a black body radiation source at Essess headquarters.

Figure 4-8. LWIR camera calibration device.



The LIDAR was calibrated by its manufacturer, Velodyne, and qualitatively verified by the contractor. Sampling frequency was optimized based on the hardware limitations of the sensors and storage systems. The contracted Imaging Team allocated a specific imaging technician to resample a subset of the data to ensure that they were internally-consistent.

## 4.5 Sampling protocol

### 4.5.1 Data description

Terabytes of thermal imaging, LIDAR and GPS data were collected at each base. For a subset of six of the buildings scanned by the drive-by method,





#### 4.5.5 Post-processing statistical analysis

Several layers of testing and data quality measurement were used at each stage of processing, from initial data acquisition to final presentation of energy analysis results. When the data capture system started, it performed sensor integrity checks, ensuring that each sensor was communicating with the main computer and sending valid data. Throughout recording, the system continued to monitor data quality, such as valid temperature ranges, image information content, GPS location, and LIDAR distance measurements. The system also monitored sensor connectivity, and raised errors if a sensor had stopped communicating. Any error or warning messages were immediately logged to a system diagnostics log and also displayed to the onboard display for the driver and navigator. At any time, a technician could log into the mobile system remotely and securely, view the images and other sensor data, and update the recording system software.

When the hard drives were imported into the secure data storage system, the import agent program ran a more rigorous data quality filter. This filter checked for data file integrity and file size, image size and information content, the frequency of each sensor message, the presence of each sensor data stream, and additional in-depth screens for GPS location noise, image pixel values, LIDAR distances and pointcloud sizes with scene distances, and thermistor readings. It also checked the data feed of sensor chamber operating conditions to make sure that the sensors were kept within specified operating temperatures. All sensor data passing these quality control checks were marked and queued for further analysis. There were few instances of unusable data caused by sudden onsets of precipitation while the team was still imaging. These data were limited and did not affect the overall analysis since the team paused the imaging until there was no precipitation.

During data processing and energy analysis, each stage of the processing pipeline passed its intermediate results through quality filters that checked for data validity, such as scene temperature readings, building metadata, GPS location consistency, raw energy flow estimates, and energy scores.

In addition to these data checks, the software behavior was tested several times a day in an automated testing environment. Each piece of processing code was built with unit tests, and integration tests checked the interaction of various software modules. The entire software infrastructure was built

with continuous integration and continuous deployment, allowing for fast feedback and agile development.

Above the normal quality control process for this study, the contractor performed outlier detection in utility consumption data to detect outliers of energy usage per square foot of building area grouped by building type. Specifically, the contractor fit elliptic envelopes of data distributions using Mahalanobis distance. The Mahalanobis distance is a way of determining the “similarity” of a set of values from an unknown sample to a set of values measured from a collection of “known” samples. It measures the separation of two groups of objects. For more information please see:

[http://www.encyclopediaofmath.org/index.php/Mahalanobis\\_distance](http://www.encyclopediaofmath.org/index.php/Mahalanobis_distance).

## **4.6 Results for Marine Corps Base Camp Lejeune, NC**

### **4.6.1 Sampling results for Marine Corps Base Camp Lejeune, NC**

The Kinetic Super-Resolution Long-Wave Infrared integrated scanning team identified 2,883 distinct feature components on 147 different buildings on Camp Lejeune out of a total of 1,307 buildings and other objects surveyed. These features were categorized by type (e.g., brick wall, roof, window glass, window frame) and surface temperature. Heat losses were calculated based on the temperatures of the features, the times of observation, the orientations of the features, and the outdoor air temperatures as described in Section 4.2 (“Baseline Characterization”).

This analysis of Camp Lejeune identified \$113,085 in potential annual building envelope-related savings across all buildings on the base for remediation measures that have a payback period of 15 years or less. These savings would require approximately \$996,669 in capital expenditures for remediation. The recommended measures include retrofitting of walls, soffits, and roof insulation and sealing leaks around windows and door-frames. Total savings from these remediation measures could save Camp Lejeune approximately \$1,696,275 over the lifetime of the projects (15 years on average), and the measures would pay for themselves after 8.8 years. This is based on the assumption that envelope-related issues and potential savings observed from the street were representative of the sides not visible from the street *on a per-building basis*.

For areas visible from the street, this analysis showed \$38,983 in potential annual building envelope-related savings across all building components

imaged with a payback period of 15 years or less. These savings would cost approximately \$333,256 in capital expenditures for remediation and a payback period of 8.5 years.

This section provides a spatial overview of results at Camp Lejeune. The second section provides a breakdown of heat loss costs and potential remediation savings by component. The third section provides a detailed analysis of 30 specific buildings on the base that have been determined to be high priority buildings. The 30 buildings were selected based on a visual and objective leak analysis, ROI potential, and Camp Lejeune's internal priorities. The fifth section discusses base-wide potential savings and costs. Chapter 5 (Performance Assessment) demonstrates the relative benefits of mobile imaging compared to traditional handheld alternatives. One building per base was selected for detailed analysis. Appendix D includes an analysis for the remaining 29 buildings.

Figures 4-10 to 4-12 show the spatial results of this analysis of conductive leaks, convective leaks and all remediation measures are found in the following paragraphs.

The conductive heat loss map represents the average dollar loss per square foot from conductive leaks, e.g., leaks of energy through walls, roofs, and other surfaces due to poor insulation. Buildings highlighted in red are the most emissive, with the highest annual additional heating and cooling load per square foot.

The convective heat loss map shown in Figure 4-11 represents the average dollar loss per square foot from convective leaks, e.g., leaks of energy through infiltration via cracks and gaps in door and window frames. Buildings highlighted in red are the most emissive, with the highest annual additional heating and cooling load per square foot.

The above payback period map (Figure 4-12) shows the combined cost effectiveness of the remediation of conductive and convective leaks expressed as a payback period (in years). Buildings in blue have an attractive payback period, while buildings in red have a less attractive payback period.

Figure 4-10. Average conductive heat loss map for Camp Lejeune.

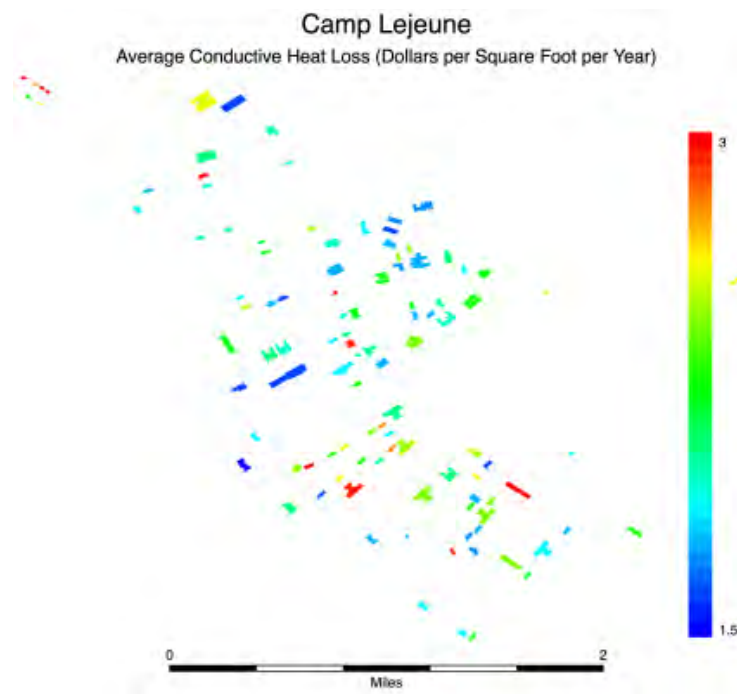


Figure 4-11. Average convective heat loss for Camp Lejeune, NC.

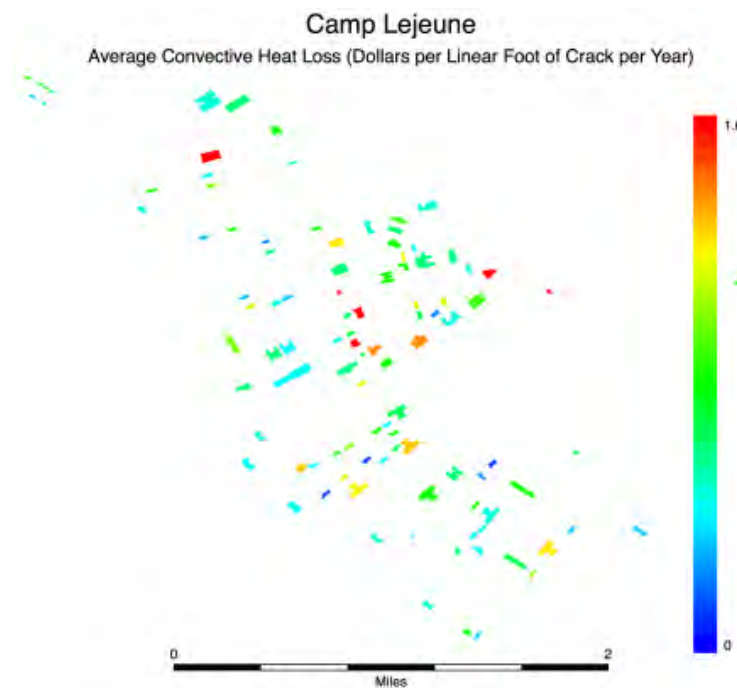
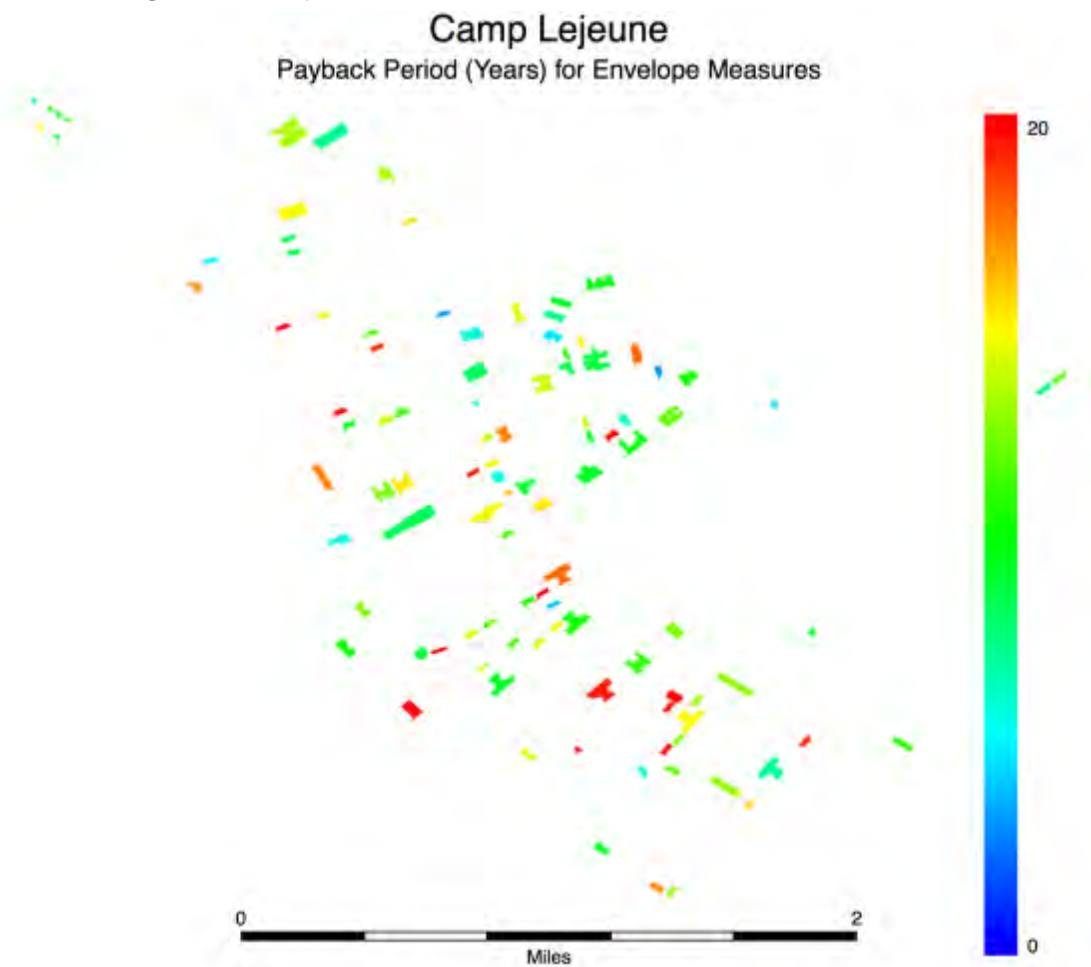


Figure 4-12. Payback period for envelope measures for Camp Lejeune, NC.



#### 4.6.2 Recommended envelope ECMs

A number of envelope ECMs are recommended for specific buildings on each base. These were determined by a combination of thermal imaging, energy consumption analysis and disaggregation, and building characteristics.

When determining the optimal envelope ECMs to recommend for a given building, the relative cost effectiveness of each ECM is compared to other available options based on the specific heat loss characteristics of the building in question. The method for calculating potential savings through envelope ECMs is characterized by a comparison of the heat flow across every hour of the year (for both cooling and heating) for an estimated current R value and a new post-remediation R value, incorporating hourly outdoor temperatures based on weather data. Air sealing-related ECMs involve a similar approach by comparing the difference between estimated current infiltration rates per linear foot of crack and post-remediation in-

filtration rates. Section 4.2 (“Baseline Characterization”) describes the technical details of how these are calculated.

The specific envelope ECMs examined include:

- *Improve Wall Insulation.* This can encompass either patching up discrete insulation holes, or improving the overall insulation of a wall through the addition of blown or sheet insulation.
- *Improve Roof Insulation.* This can encompass either patching up discrete insulation holes, or improving the overall insulation of a roof/ceiling through the addition of blown or sheet insulation.
- *Improve Soffit Insulation.* Soffits are the junction between walls and roofs and are often poorly insulated. In many cases they can be accessed and have their insulation improved.
- *Improve Exposed Basement Wall Insulation.* When buildings have part of their basement wall exposed, they can often benefit from installing insulation on the portion exposed to the air.
- *Seal Window Frame Leaks.* This involves using caulk or weather-stripping to seal cracks in window frames that are letting air in or out of the building.
- *Seal Door Frame Leaks.* This also involves using weather-stripping (and in some cases caulk) to reduce the size of gaps around doorframes while not hindering the operation of the door.

Window and door replacement are not recommended because they are generally not cost effective, especially in military facilities, where security requirements can increase the cost of window and door installations.

## **5 Performance Assessment**

### **5.1 Relative cost effectiveness of handheld and mobile imaging methods**

#### **5.1.1 Handheld method**

- Each building takes about 25 minutes of imaging work; necessary to overlap building components in each frame.
- Handheld unit is a FLIR i7 (The FLIR i-Series cameras are handheld thermal cameras specially designed for building diagnostics and commonly used in residential and commercial thermal audits).
- 140x140 pixels.
- 29 by 29 degree field of view (FOV).
- Spotmeter, area with max/min. temperature, isotherm above/below.
- Scanning Cost: \$840,000. Based on the amount of building space imaged, the estimated cost is ~ \$1,000 per 5,000 sq ft of floor space.

#### **5.1.2 KSR LWIR method**

- Each building takes about 30 seconds to scan
- Mounted in integrated system camera
- 640x512 pixels
- 45x37 degree FOV
- Temperature calculated per feature
- Material emissivity obtained by computer vision
- Scanning Cost: Set cost at \$200,000 per installation, regardless of square footage

The KSR LWIR approach provides a number of significant advantages over conventional handheld infrared thermography, both in terms of the speed and cost of imaging and the quality and utility of the images and analysis.

Handheld radiometric imaging instruments are standard equipment for energy efficiency measurements of building envelopes. The use cases for these imagers are low throughput, non-quantitative work. Data are stored on a low speed secure digital (SD) card. Image contrast is tuned for visual use. The center point of reported temperatures is what is outputted to the

user. Resolution typically ranges from 80 x 80 pixels to 150 x 150 pixels. The FOV is 30 x 30 degrees.

The Kinetic Super-Resolution Long-Wave Infrared integrated scanning system uses multiple radiometric thermal cameras. These devices are designed for high-throughput analytical and computer vision work. The devices are configurable through computer control and automation. Data flows from devices over a high speed local network to high speed redundant storage. Raw digital number information is stored for each image frame. Resolution per camera is 640 x 512 pixels. The field of view per camera is (FOV) 37 x 45 degrees while the total field of view is 37 x 80 degrees.

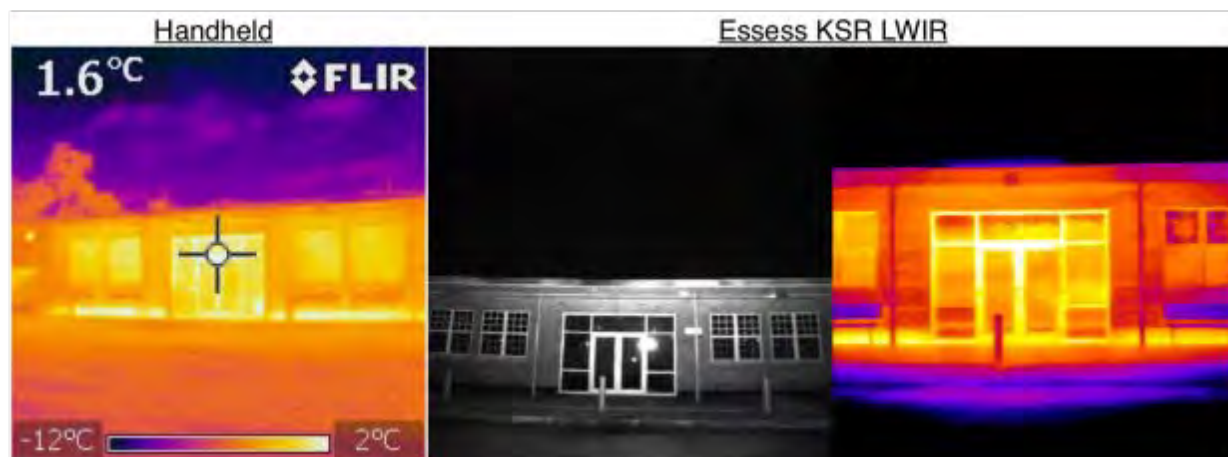
Images can be acquired at a much faster rate using the Essess sensor system. There is continuous acquisition without the need to frame the building. Each frame contains overlapping information. Further, the raw information allows temperature conversions to be done per individual region in the frames versus just one temperature point in the handheld instrument. The Essess system also provides near infrared images associated with each long-wave infrared image. These provide the ability to distinguish features and textures that may not be easily visible in the long-wave infrared image, as the near infrared image is similar to a conventional photograph (Figure 5-1).

### **5.1.3 Example performance in Camp Lejeune Bldg 235 (Bus Station)**

The resolution and FOV of the handheld unit is not nearly as good as the cameras employed in the vehicle scanning system (Figure 5-1). The resolution is 15 times higher in the cameras used on the Essess scanning system. The FOV of the scanning system is higher. Due to multiple overlapping features and high acquisition speed, the effective FOV is exceedingly high.



Figure 5-1. Handheld thermographic image versus Essess KSR LWIR thermographic image for Bldg 235, Camp Lejeune, NC.



#### 5.1.4 Summary

After a one-to-one comparison of handheld imaging against the vehicle scanning system, it is clear that the mobile imaging system is capable of collecting thermal imaging data in a far more scalable and efficient manner than traditional handheld thermography. Furthermore, the Essess imaging rig is equipped with multiple sensors including near infrared cameras and LIDAR, which, when combined with LWIR, allows significantly more information gathering than would be possible using traditional thermography. This includes building façade data and building orientation.

The automated data processing system also allows an efficient and accurate analysis of each image, which contributes to detailed, accurate reporting. This type of quantitative analysis is not possible using the handheld system as it is impossible to accurately quantify how much energy is leaking out of one area of a building versus another area. In terms of speed, resolution, and FOV, Essess' scanning system exceeded the handheld unit by a significant margin.

## 5.2 Comparison of the fidelity and usefulness of imagery at varying scanning distances

Essess scanned six buildings with each building being imaged from different distances starting at 20 yards and ending at 180 yards. The resulting data showed that there is very little difference in the measured building temperature for the entire building from 20 yards versus 180 yards ( $\pm$

0.16 °F). Figure 5-2 shows that the first pass occurred at approximately 20 yards from the building with each succeeding pass being approximately 20 yards further from the building.

Although the distance between the cameras and the building appears to have very little effect on the system's ability to measure building surface temperatures, building feature recognition becomes more difficult as you increase the distance from which the building is scanned. Individual building leaks also become gradually less visible as the distance is increased (as seen in the images below).

Figure 5-2. Building surface temperature vs. scene distance: Temp =  $23.7 \pm 0.16$  °F.

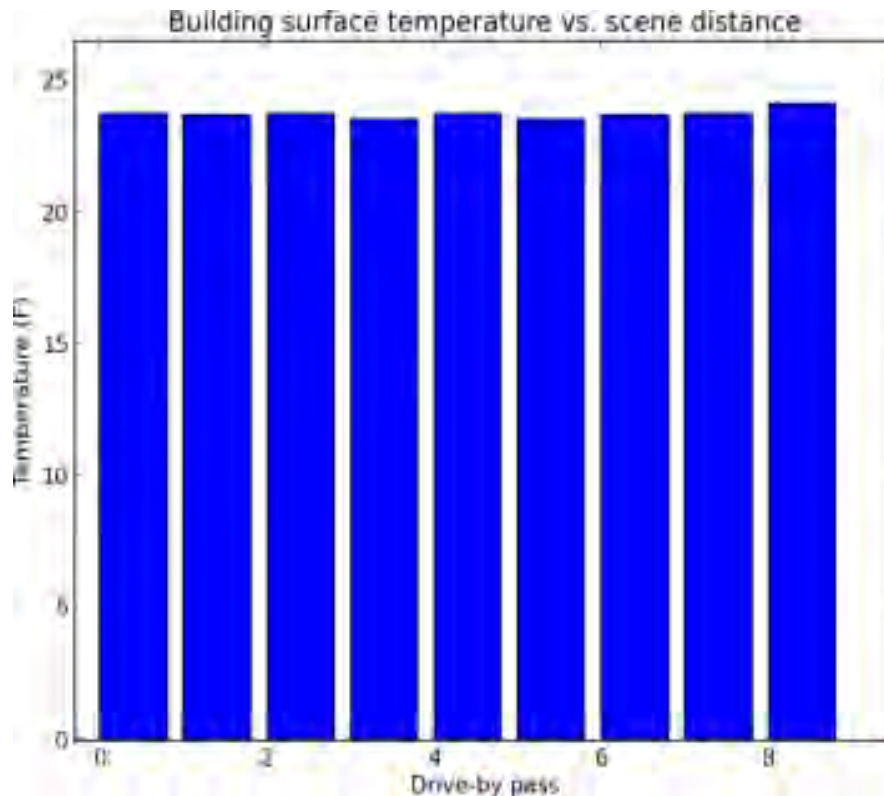
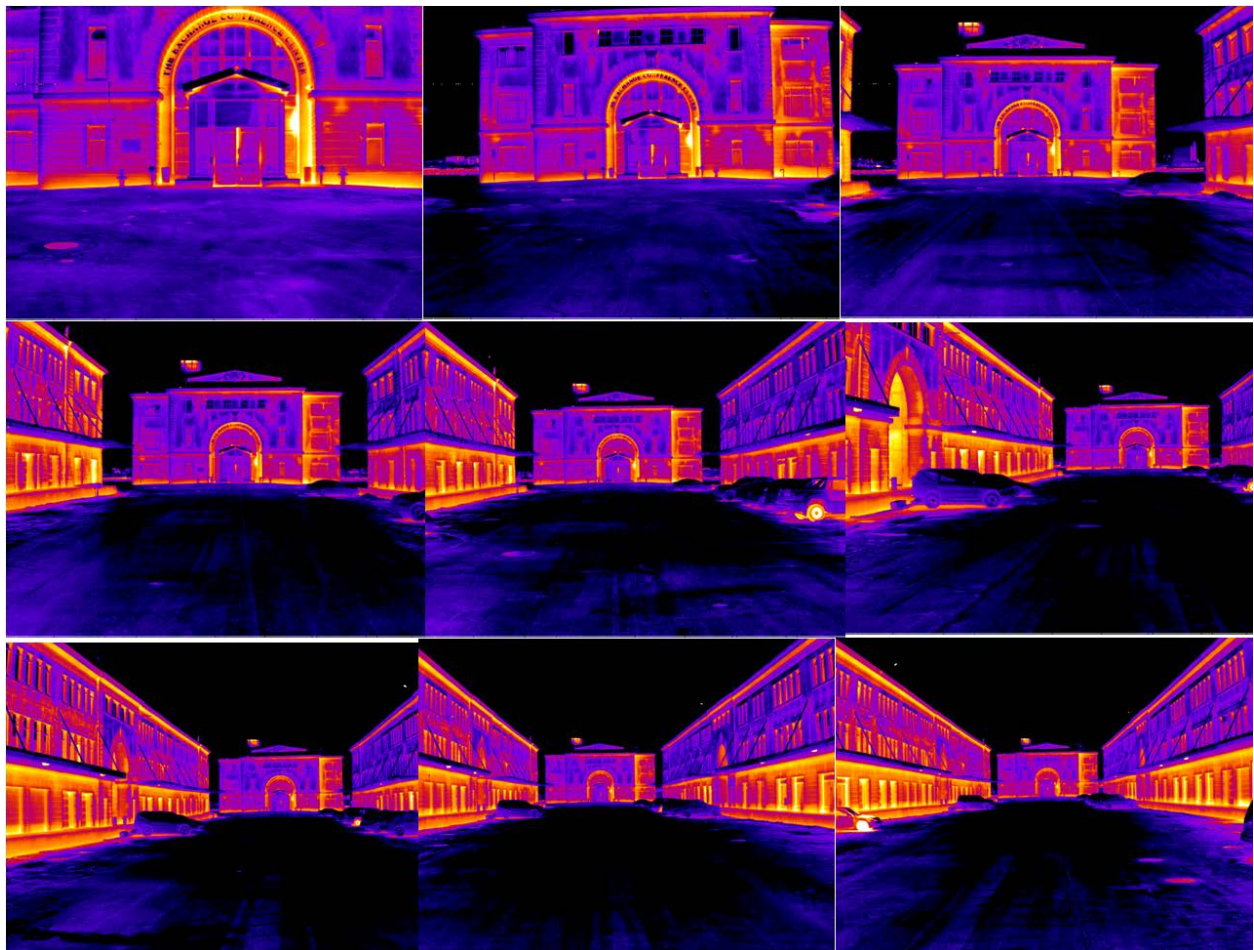


Figure 5-3. Assess LWIR distance test (from left to right) Row 1: 20 yards, 40 yards, 60 yards; Row 2: 80 yards, 100 yards, 120 yards; Row 3: 140 yards, 160 yards, 180 yards



## 5.3 Actionable results

### 5.3.1 Detailed analysis for Bldg 1, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 36,832

**Average Daily Electric Use:** 2,166 kWh

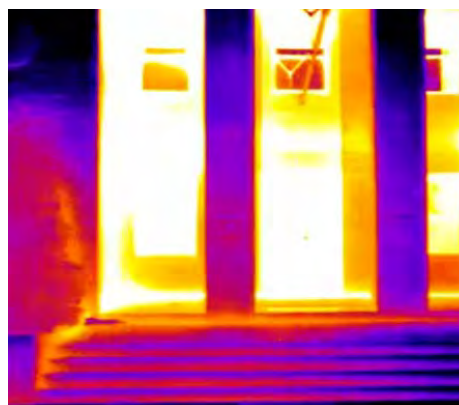
**Electricity Score:** 80<sup>th</sup> Percentile`

Bldg 1 (Figures 5-4 and 5-5) has an electricity usage of 21.5 kWh per square foot per year.

Figure 5-4. Aerial view of Bldg 1, Camp Lejeune.



Figure 5-5. Thermal image of Bldg 1, Camp Lejeune.



The electricity and gas scores above compare the building to similarly sized buildings of the same type on an energy use per square foot basis. An energy score at the 100<sup>th</sup> percentile represents the highest energy use per square foot relative to similar buildings, while a score at the 0<sup>th</sup> percentile represents the lowest. The annual cooling and heating loads are calculated by regressing natural gas bills and electric bills (when available) against degree days for each billing period to disaggregate the heating and cooling components of building energy use.

Figure 5-6 shows an abatement curve for all identified remediation measures for the building in question. Each bar represents a distinct remediation. The width of the bars represents the savings potential, while the height represents the economic viability (represented by ROI). The height of each bar shows how many dollars of savings may be expected for every \$1 spent on the remediation measure.

Table 5-1 lists the recommended envelope ECMs.

Figure 5-6. ECM savings for Bldg 1, Camp Lejeune, NC.

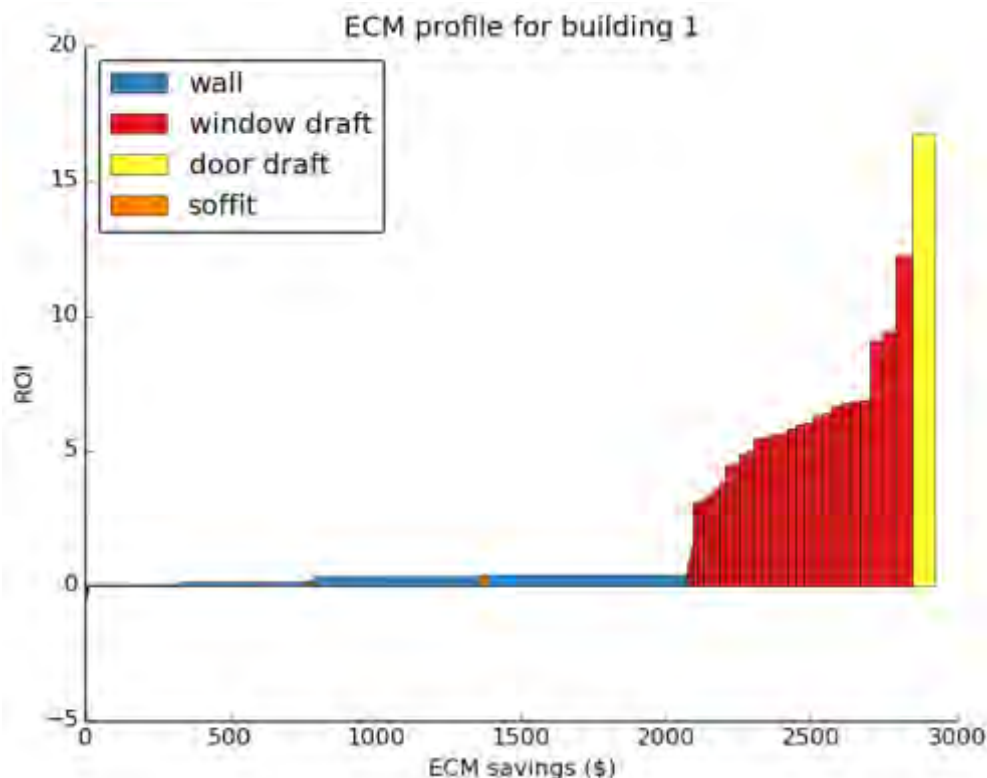


Table 5-1. Envelope ECMs, Bldg 1, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	3161	3096	2003	24240	12.1
Seal Window Frame Leaks	1244	1218	788	2069	2.6
Seal Door Frame Leaks	120	118	76	65	0.8
Improve Soffit Insulation	79	77	50	583	11.7

Annual potential remediation savings for this building are \$2,918 for a simple payback of 9.2 years for this package of envelope-related ECMs.

The brick wall at timestamp 323:17 in the online drive-by application is highly emissive. There are some insulation holes around the middle of the wall (Figure 5-7), and the overall surface appears poorly insulated compared to other walls on the base (Figure 5-8).

The wall at timestamp 323:22 is also highly emissive, and has some apparent insulation holes near the middle of the wall. The soffit is also fairly emissive, and the window frames in the upper left are potentially leaky.

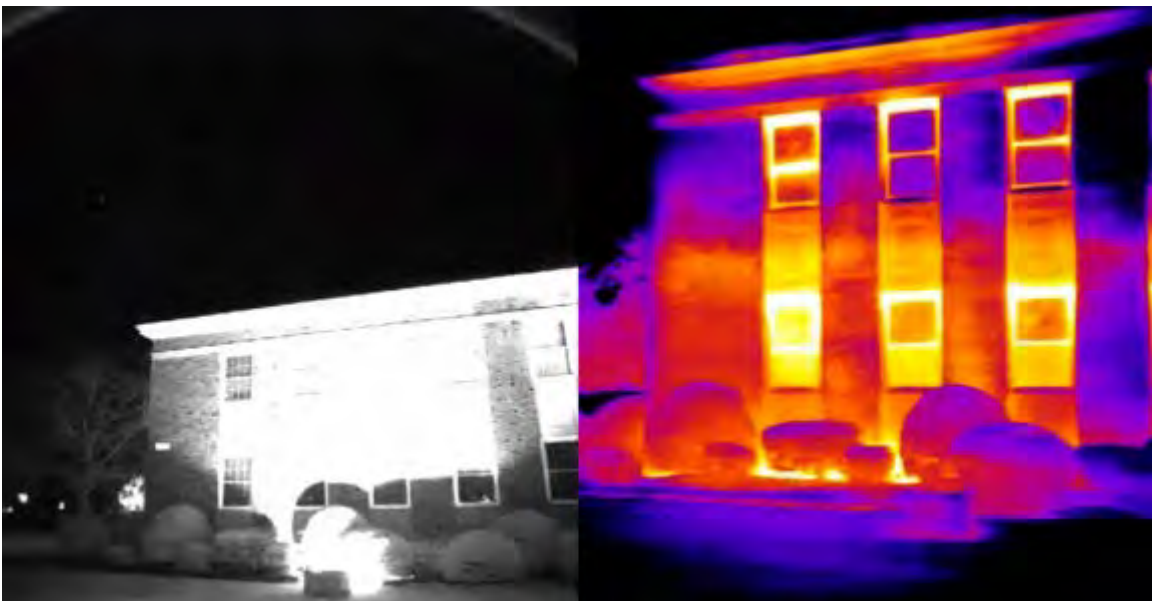


### 5.3.2 Notable leaks

Figure 5-7. Insulation holes in Bldg 1, Camp Lejeune, NC.



Figure 5-8. Additional wall insulation holes in Bldg 1, Camp Lejeune, NC.



### 5.3.3 Portfolio strategy analysis for Marine Corps Base Camp Lejeune, NC

The analysis of Camp Lejeune thermal imaging data estimates \$113,085 in potential annual building envelope-related savings across all buildings on the base for remediation measures that have a payback period of 15 years or less. These savings would require approximately \$996,669 in capital expenditures for remediation. The recommended measures include retrofit-

ting of walls, soffits, and roof insulation and sealing leaks around windows and doorframes. Total savings from these remediation measures could save the military approximately \$1,696,275 over the lifetime of the projects (15 years on average), and the measures would pay for themselves after 8.8 years.

These base-level savings are estimated by dividing the calculated savings for each building by the percent of the building imaged, assuming that the portions of the building not imaged are similar in characteristics (R-values, infiltration) to the portion imaged. The area of the buildings captured in the thermal images from the street identified \$38,983 in savings from discrete building component leaks, at a cost of \$333,256 and with a payback period of 8.5 years. The total savings over the lifetime of the envelope remediation projects identified in the thermal images was \$584,749.

Table 5-2 lists the potential savings and payback period for each category of remediations for all imaged buildings on Camp Lejeune, NC.

Of all envelope remediation options examined, air sealing of doors and window frames tend to be the most cost-effective, with a typical payback period of 3.7 years for door frames and 5.1 years for window frames. The table below shows both estimated base-wide potential savings for identified components and the payback period for all measures considered.

Table 5-2. All recommended remediations, Camp Lejeune, NC.

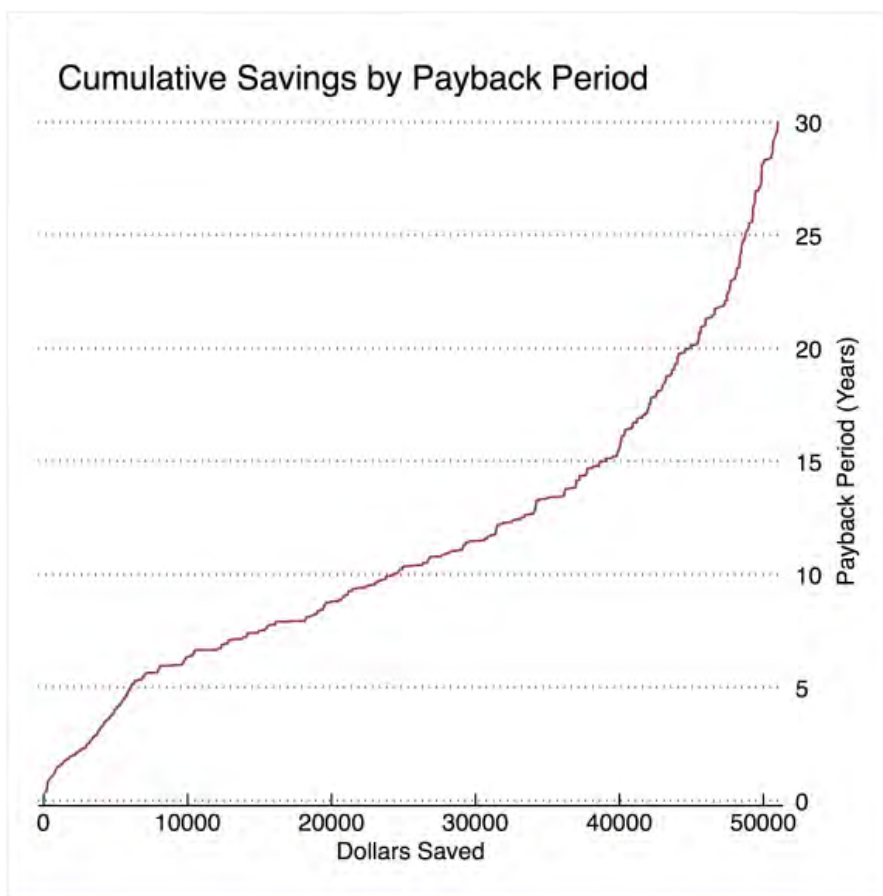
Measure	Potential Savings	Payback Period
Seal Door Frame Leaks	\$2,695	3.7
Seal Window Frame Leaks	\$7,081	5.1
Basement Wall Insulation	\$1,262	9.6
Improve Wall Insulation	\$26,395	9.7
Improve Soffit Insulation	\$952	10.7
Improve Roof Insulation	\$598	14.0
Occupancy Sensors	\$105,440	0.7
Low Flow Showerhead	\$552	1.7
LED Exit Signs	\$30,874	2.2
Replace Incandescent Bulbs with CFLs	\$943	2.6
Smartstrips	\$267	5.9
Efficient Fluorescent Lights	\$235,126	9.8

A significant portion of envelope-related remediation savings comes from improving wall insulation. This is to be expected, as walls comprise the majority of the surface area of most buildings on the base. Wall insulation retrofits can be cost-effective for the more emissive surfaces, and the thermal imaging data can help provide an essential pre-assessment to determine the surfaces to target for improvements.

The total savings available at each different payback period may be examined by reviewing the cumulative savings across all measures by payback period (Figure 5-9).

There are potential annual envelope-related remediation savings from imaged surfaces with a payback period of less than 5 years, over \$24,000 in savings with a payback of less than 10 years, and over \$39,000 in savings with a payback of less than 15 years.

Figure 5-9. Cumulative savings by payback period.





### 5.3.4 Recommendations for Marine Corps Base Camp Lejeune, NC

Table 5-3 lists the high-impact cost-effective remediation measures that base planners should target first. These are primarily wall insulation-related measures for the buildings identified as the most emissive.

These 30 measures would collectively save an estimated \$11,904 per year at a cost of \$144,508 with a payback period of 12.1 years. Figure 5-10 to 5-17 show the specific location of all 30 immediately actionable recommendations. Note that only the primary features (e.g., the brick walls) are analyzed in the images. Obstructions like trees or flagpoles as well as unrelated features like garage doors or windows are excluded.

**Table 5-3. Immediately actionable remediations for Camp Lejeune, NC.**

Label No.	Bldg No.	Action	Material	Init R Value	New R Value	Savings (\$)	Cost (\$)	Payback (yrs)
1	2600	Improve Wall Insulation	Brick	8.5	13.6	1101	8727	7.9
2	895	Improve Wall Insulation	Brick	9.9	13.7	888	11929	13.4
3	HP210	Improve Wall Insulation	Brick	8.1	13.6	714	5094	7.1
4	8	Improve Wall Insulation	Brick	9.5	13.7	715	8219	11.5
5	1	Improve Wall Insulation	Brick	9.3	13.6	681	7345	10.8
6	401	Improve Wall Insulation	Brick	9.2	13.6	592	6155	10.4
7	1	Improve Wall Insulation	Brick	9.4	13.7	568	6272	11.1
8	HP104	Improve Wall Insulation	Brick	9.0	13.6	486	4568	9.4
9	62	Improve Wall Insulation	Brick	10.4	13.6	327	5542	16.9
10	407	Improve Wall Insulation	Brick	9.3	13.6	331	3480	10.5
11	20	Improve Wall Insulation	Brick	10.1	13.6	317	4756	15.0
12	1	Seal Door Frame Leaks	D Frame	N/A	N/A	76	65	0.8
13	1826	Improve Wall Insulation	Siding	8.4	10.0	518	11315	21.9
14	2905	Improve Wall Insulation	Siding	7.9	10.0	352	5211	14.8
15	2603	Improve Wall Insulation	Brick	9.7	13.6	360	4470	12.4
16	8	Improve Wall Insulation	Brick	10.5	13.6	262	4666	17.8
17	18	Improve Wall Insulation	Brick	10.8	13.7	244	4832	19.8
18	424	Improve Wall Insulation	Brick	8.3	13.6	243	1833	7.5
19	430	Improve Wall Insulation	Brick	9.6	13.5	240	2936	12.2
20	8	Improve Wall Insulation	Brick	9.6	13.6	242	2837	11.7
21	408	Improve Wall Insulation	Brick	9.4	13.6	214	2369	11.1
22	2917	Improve Wall Insulation	Siding	7.8	10.0	273	3762	13.8
23	2913	Improve Wall Insulation	Siding	7.9	10.0	388	5569	14.4
24	235	Improve Wall Insulation	Brick	8.5	13.6	229	1860	8.1
25	217	Improve Wall Insulation	Brick	10.3	13.7	211	3203	15.2
26	2903	Improve Wall Insulation	Siding	7.7	10.1	498	6119	12.3
27	2600	Improve Wall Insulation	Brick	9.8	13.7	257	3253	12.7
28	408	Improve Wall Insulation	Brick	10.1	13.7	184	2608	14.2
29	2600	Improve Soffit Insulation	Soffit	8.9	13.6	58	571	9.9
30	2613	Improve Roof Insulation	Roof	10.8	15.0	336	4942	14.7

Figure 5-10. Camp Lejeune Bldgs 2600 (upper left), 895 (upper right), HP210 (lower left) and 8 (lower right).

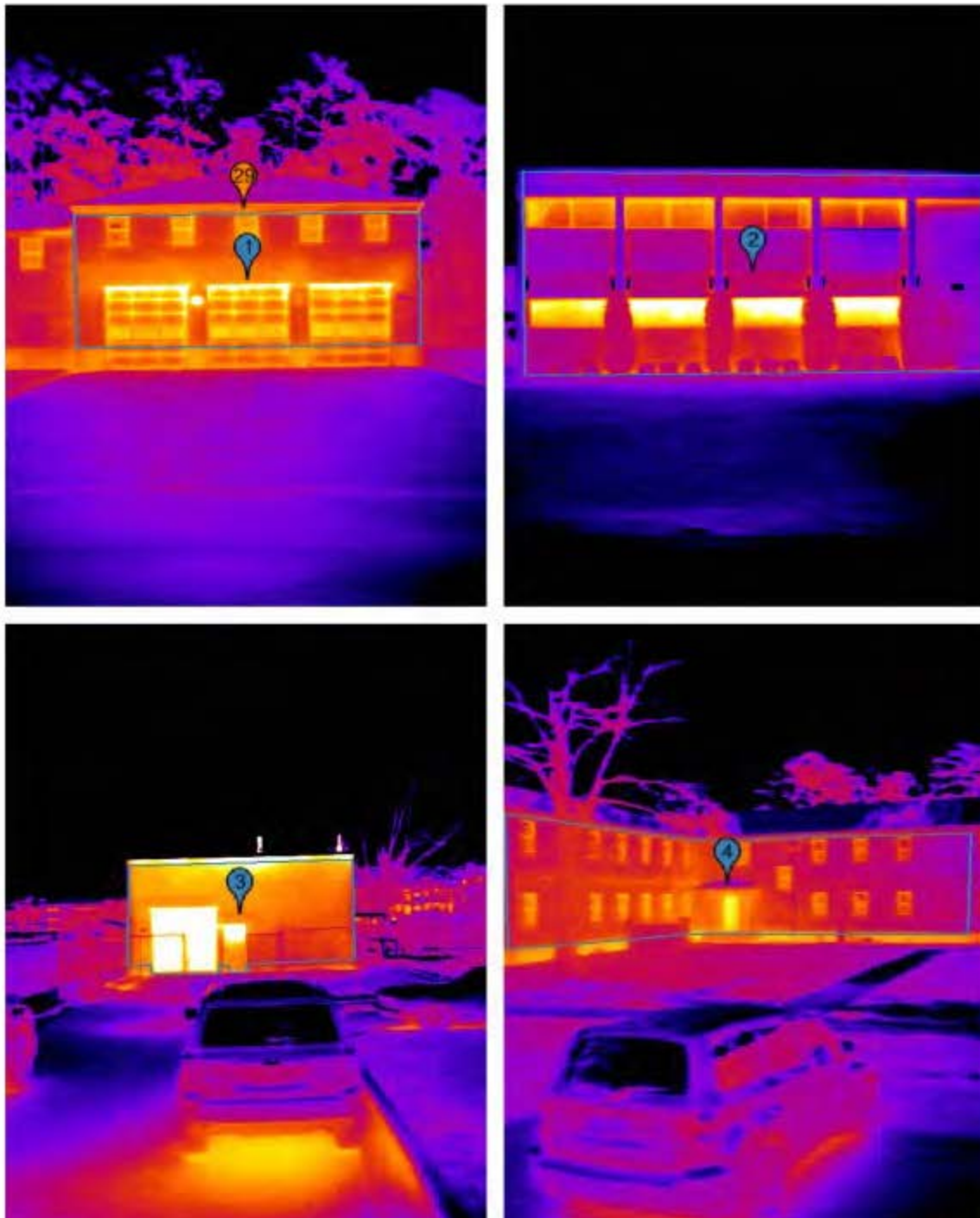


Figure 5-11. Camp Lejeune Bldgs 1 (upper left), 401 (upper right), 1 (lower left) and HP104 (lower right).

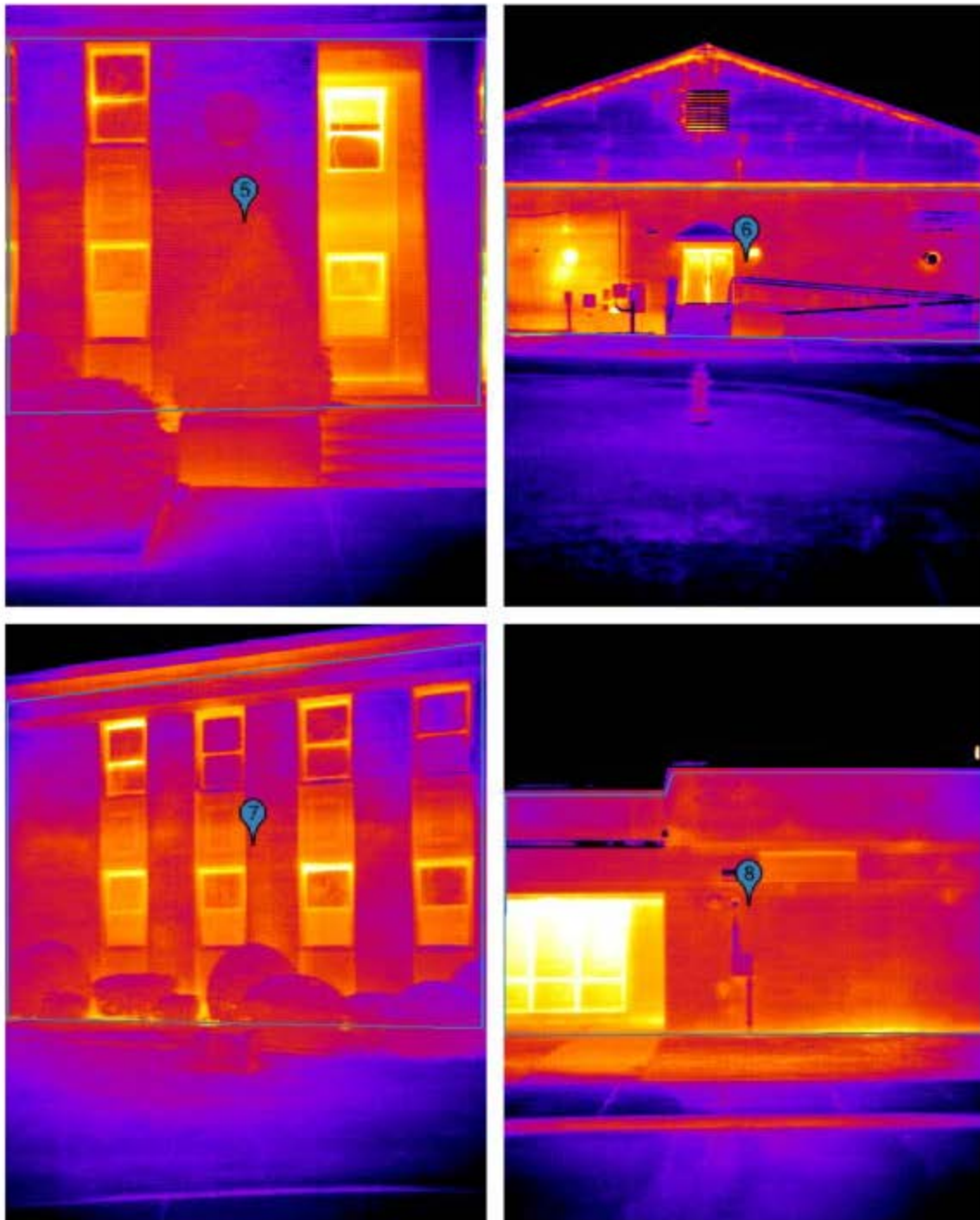


Figure 5-12. Camp Lejeune Bldgs 62 (upper left), 407 (upper right), 20 (lower left) and 1 (lower right).

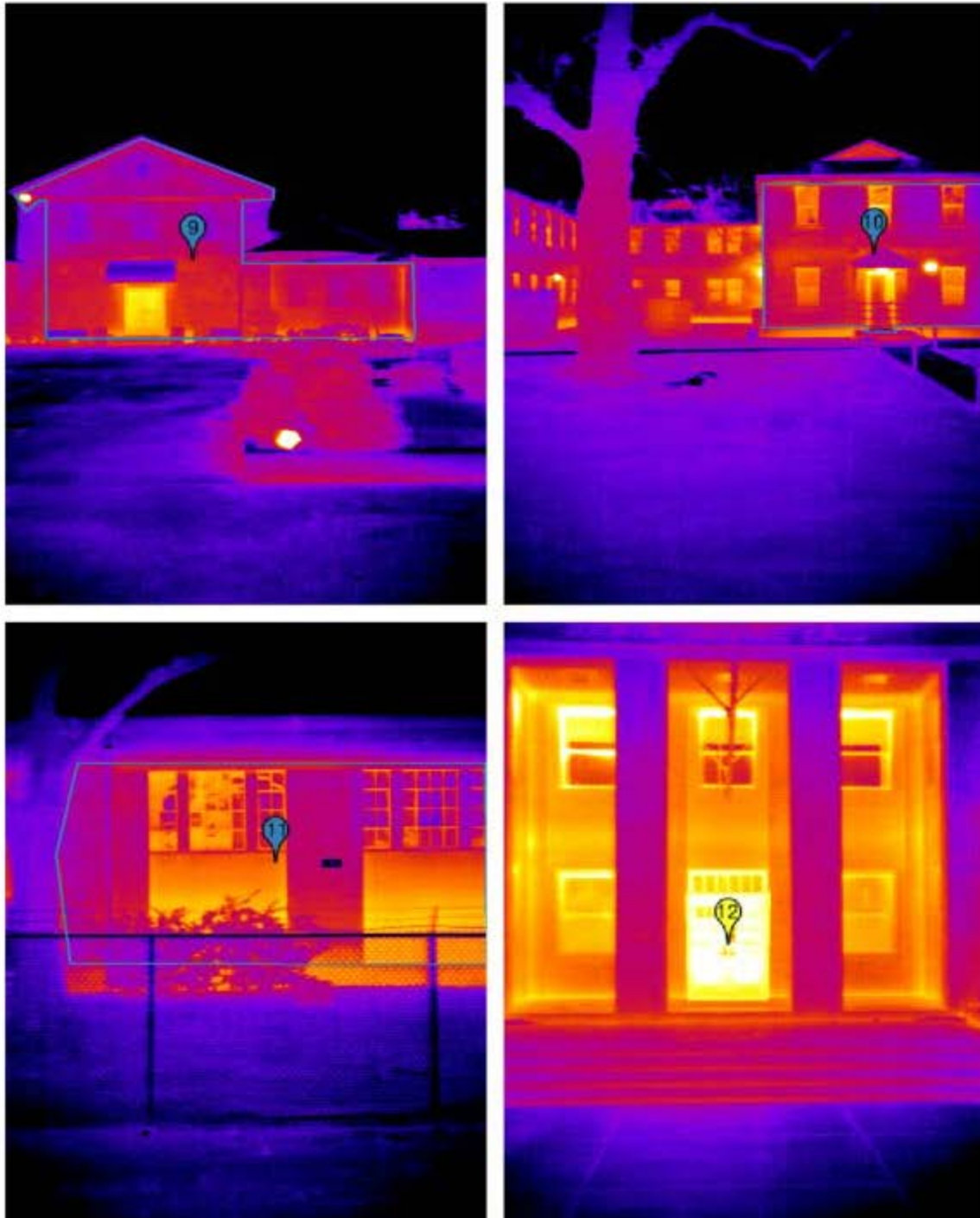




Figure 5-13. Camp Lejeune Bldgs 1826 (upper left), 2905 (upper right), 2603 (lower left), and 8 (lower right).

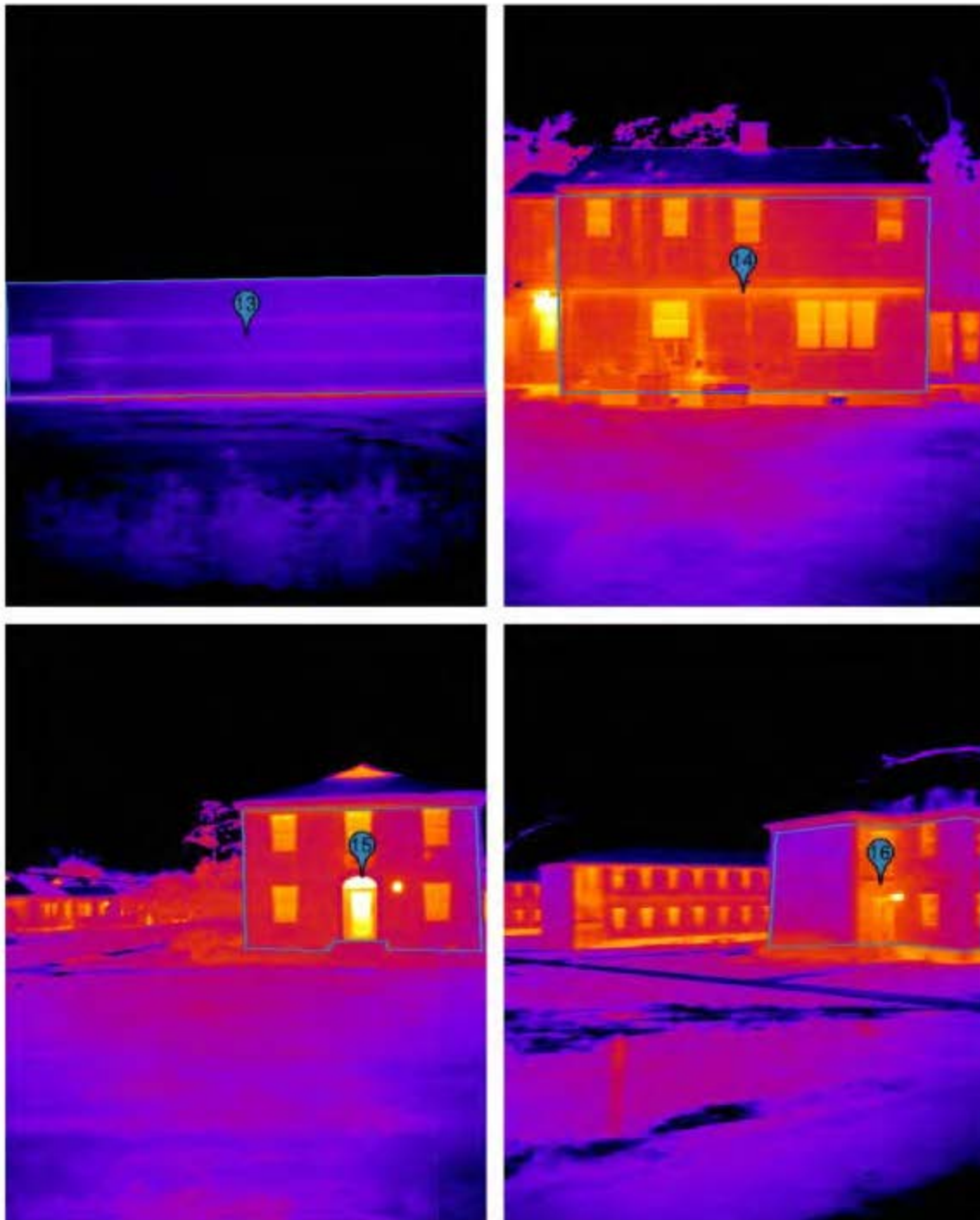


Figure 5-14. Camp Lejeune Bldgs 18 (upper left), 424 (upper right), 430 (lower left) and 8 (lower right).

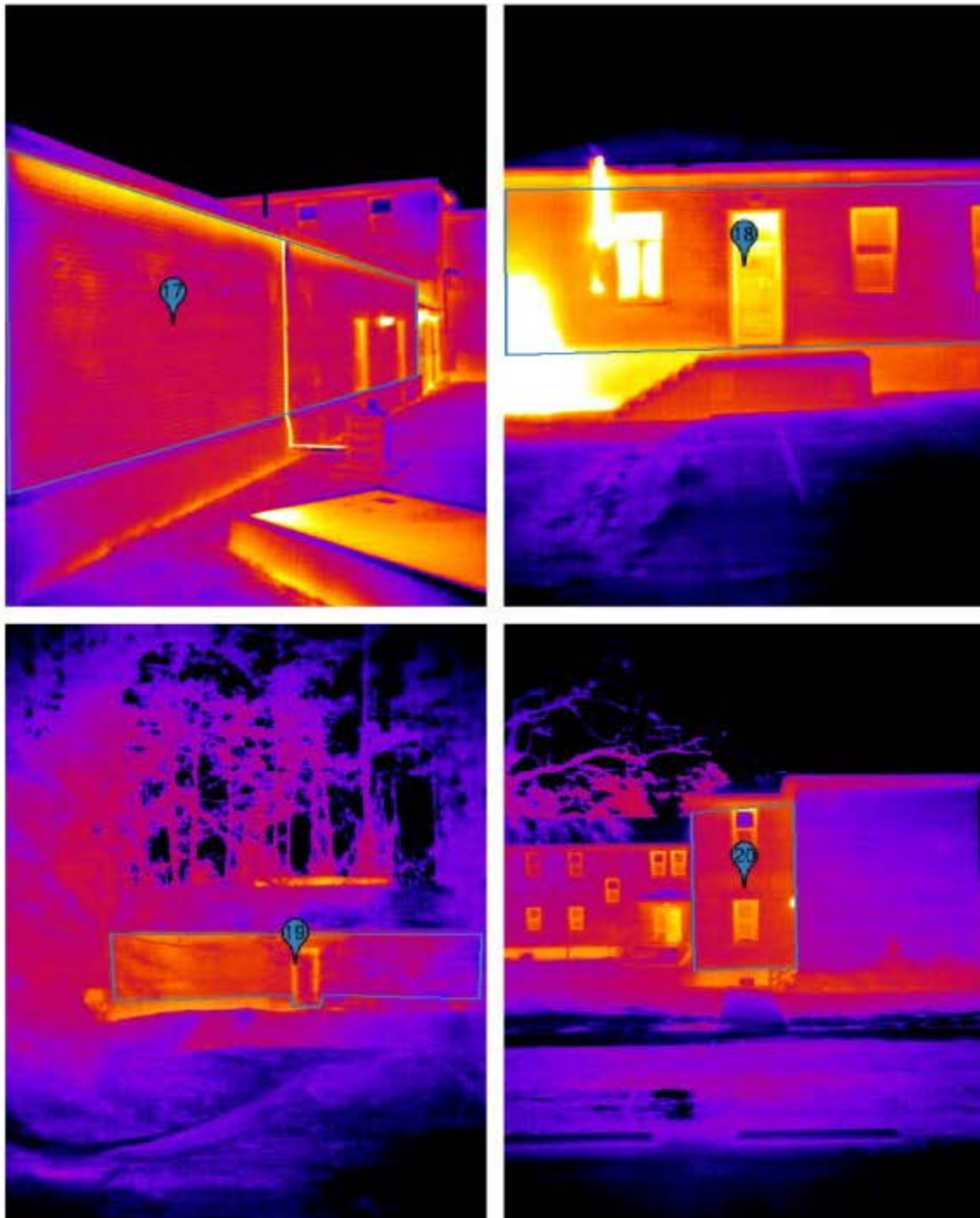


Figure 5-15. Camp Lejeune Bldgs 408 (upper left), 2917 (upper right), 2913 (lower left), and 235 (lower right).

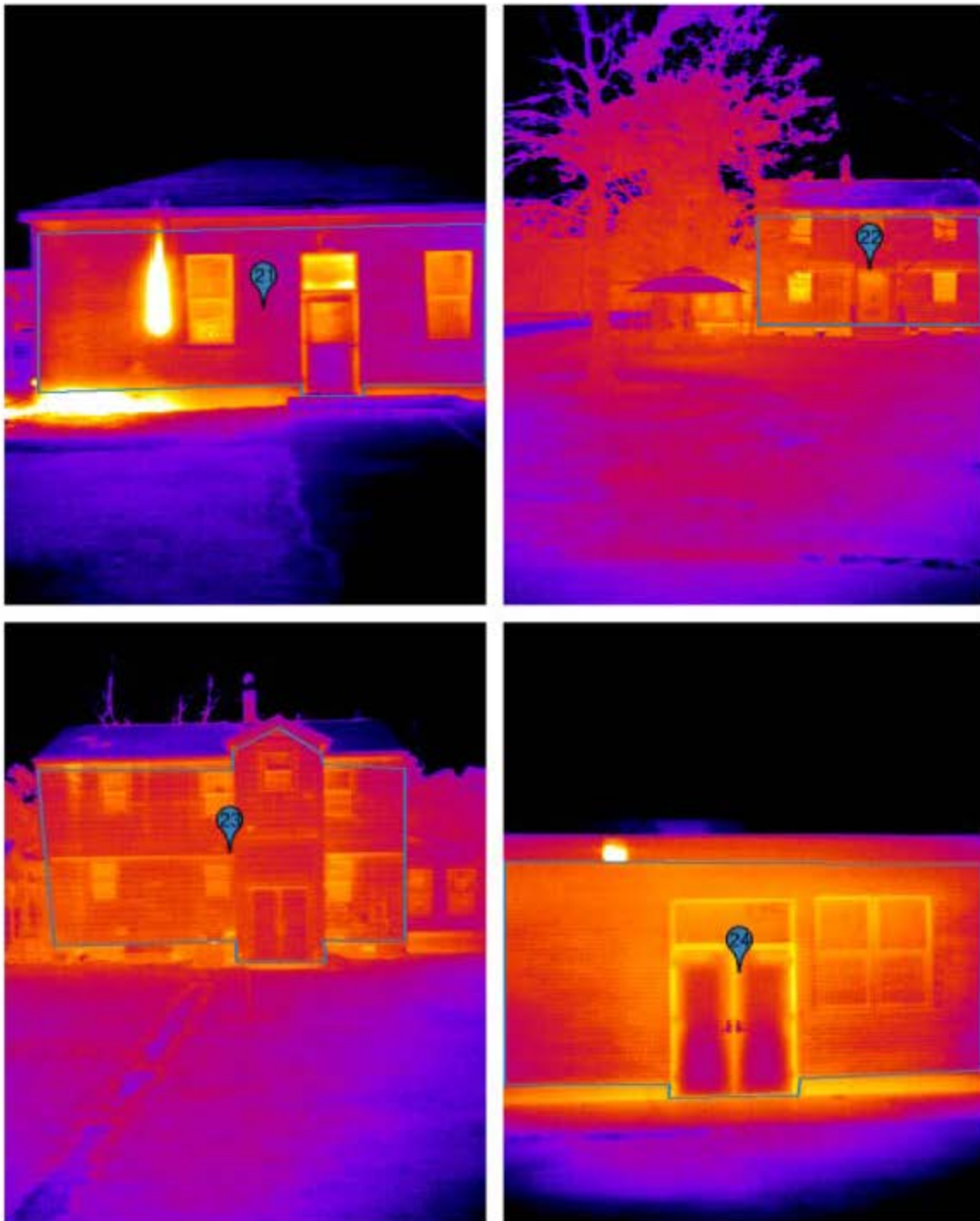




Figure 5-16. Camp Lejeune Bldgs 217 (upper left), 2903 (upper right), 2600 (lower left), and 408 (lower right).

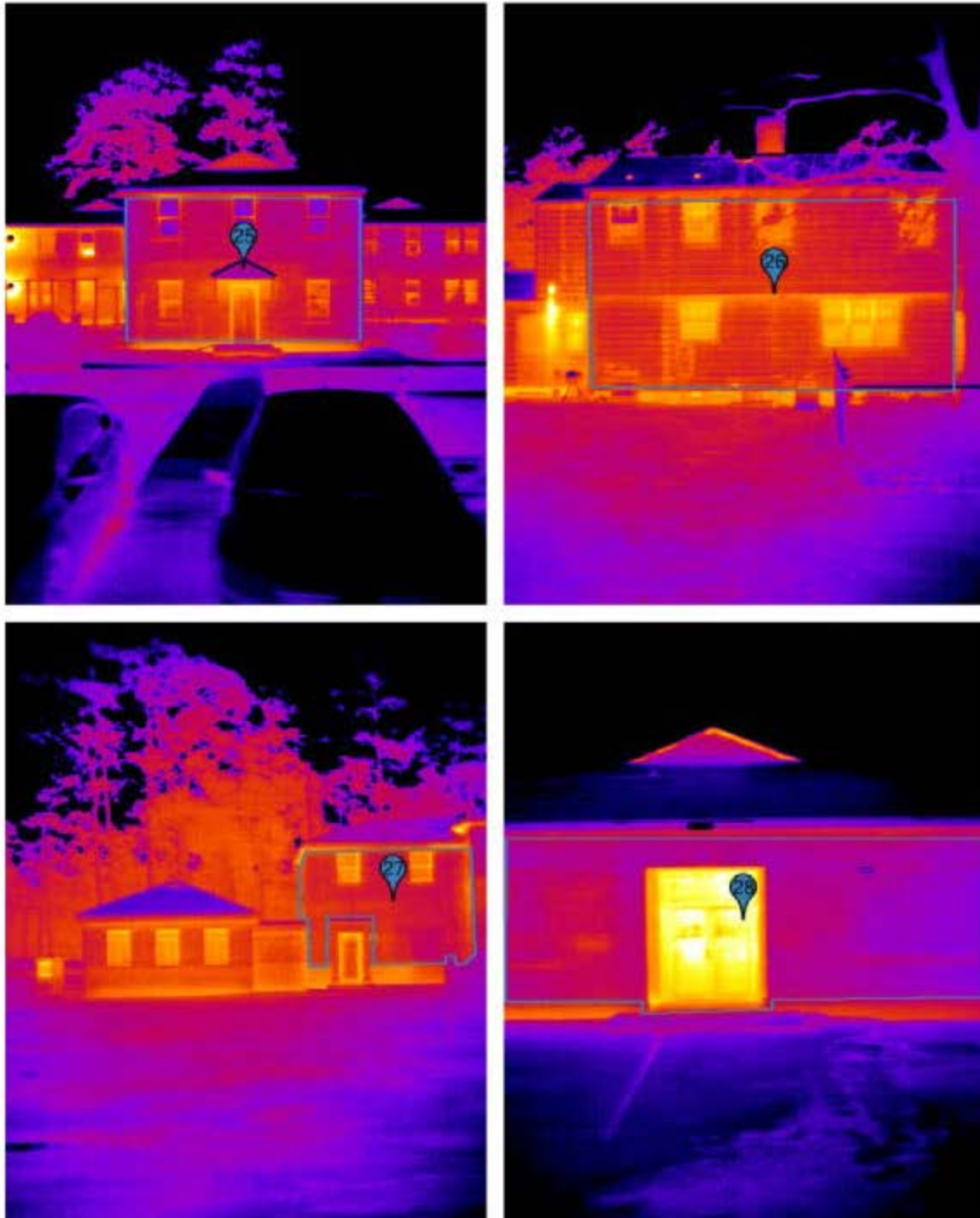




Figure 5-17. Camp Lejeune Bldg 2613.



## 6 Cost Assessment

The total cost for scanning, analyzing and producing a report for the two sites included in this demonstration (Camp Lejeune and Scott AFB) was \$404,577. For the purposes of this demonstration (and to adhere to the guidelines set forth in the Broad Agency Announcement) both installations were treated as a single project and the costs were broken up by phases rather than a per-building cost. Figure 6-1 shows the itemized cost breakdown.

Figure 6-1. Essess cost summary for scanning, analysis and reporting for Camp Lejeune, NC and Scott AFB, IL.

**Essess, Inc.  
Budget Summary**

// ----- Two Phases ----- //				
	Phase One(1)	Phase Two(2)	Phase Three(3)	Total Phases One thru Three
Direct Labor	\$33,392	\$44,144	\$30,008	\$107,544
Fringe Benefits	\$2,109	\$2,732	\$1,707	\$6,547
Equipment Costs	\$0	\$0	\$0	\$0
Expendable Supplies	\$0	\$0	\$0	\$0
Travel	\$0	\$9,781	\$0	\$9,781
Subcontracts	\$38,400	\$72,000	\$48,000	\$158,400
Other Direct Costs	\$0	\$0	\$0	\$0
Indirect Costs	\$29,821	\$39,376	\$26,641	\$95,837
	\$103,721	\$168,032	\$106,356	\$378,109
Operating Margin (7%)				\$26,468
Total Budget				<u><u>\$404,577</u></u>

**Notes:**

- 1) See "1. Phase One Budget" for details
- 2) See "2. Phase Two Budget" for details
- 3) See "3. Phase Three Budget" for details
- 4) See "4. Phase Four Budget" for details
- 5) See "5. Phase Five Budget" for details
- 6) See "6. Phase Six Budget" for details

### 6.1 Cost model

The subtasks accomplished in each phase are outlined in detail in Section 4.1.6 ("Test Phases," p 21). For all three phases, the majority of the costs were for direct labor and contracting Subject Matter Experts for computer vision aided data processing using commercial thermography and energy modeling. Phase 1 costs related to the customization of the imaging hard-

ware and creating logistics software for the driving team to navigate while imaging. To capture data in the most efficient manner, the driving team was guided by an onboard navigation system with route guidance based on the installations' street network. This must be created for each base, as complete road network information for military installations is rarely publicly available. For Camp Lejeune and Scott AFB the Phase 1 costs were \$103,721 (Figure 6-1).

Phase 2 costs were related to data capture and analysis. Essess drove the imaging vehicle to Camp Lejeune and captured thermal, NIR, LIDAR, and GPS data. Once the data were sent to Essess headquarters, it was processed (the raw data were converted into temperature images and the temperature images were correlated to the correct GPS coordinates based on vehicle GPS and military provided GIS information). After the data were processed, the second part of Phase 2 analyzed the processed data to detect building thermal inefficiencies and leaks in the building envelope. The contractor also built an online drive-by application to enable Energy Managers at Camp Lejeune select buildings for further analysis. The total cost for Phase 2 was \$168,032.

Phase 3 consisted of aggregating the mobile thermal imaging results, analyzing the handheld thermography data, and preparing this report. The total cost for Phase 3 was \$106,356.

Table 6-1 lists "model" costs for a single military installation. Essess could image hundreds of bases in a single winter while maintaining the same cost structure making the technology significantly more scalable.

Table 6-1. Cost model for imaging a military installation.

Cost Element (for single military installation)	Estimated Costs
Phase 1: Hardware Customization and Logistics Software Optimization	\$51,861
Phase 2: Data Capture, processing and Analysis	\$81,567
Phase 3: Aggregating analyzed data in a report format	\$50,744

## 6.2 Cost drivers

There are no major cost drivers for this technology as it is applicable to military bases across various ASHRAE Climate Zones. The technology is efficient and scalable, which allows Essess to image significantly larger installations without increasing the cost structure. However, unlike a typical

auditor that charges per building, Essess' cost structure is on a per installation basis. This is due to the fact that the bulk of Essess' costs are front-loaded. Once the imaging rig is deployed to an area, there is only a marginal cost in imaging 100 buildings versus 1,000 buildings.

### **6.3 Cost analysis and comparison**

Essess' thermal imaging, data processing, data analysis and reporting costs are roughly \$200,000 per military installation. As described in the Section 6.1 ("Cost Model," p 64), the operational implementation of the technology requires significant customization to the hardware rig and to the logistics, processing and analysis software. The data in Chapter 5 ("Performance Assessment") provide a detailed description of each remediation recommendation and also provides the life-cycle costs for each remediation. The end result is valuable energy efficiency data and remediation recommendations.

Traditionally, the only way to get envelope efficiency information for each building was to use a handheld thermal camera on each building. However, handheld thermography is relatively very inefficient and also requires a human to interpret each image whereas Essess has the ability to automatically analyze thousands of thermal images. Furthermore, commercial energy audits that include envelope thermal imaging using handheld thermography typically cost around \$1,000 for a 5,000 sq ft building and \$10,000 for a 50,000 sq ft building. Essess imaged 4.2 million sq ft of building space at Camp Lejeune. Essess imaged, processed and analyzed data and developed reports for both military installations for \$404,577. Based on the costs above, having the same amount of building space analyzed with a handheld camera would cost approximately \$840,000. That is \$1,355,423 more than Essess' mobile imaging costs.

## 7 Implementation Issues

The Essess imaging rig is proprietary technology that was deployed based on a licensing model so there was (and will be) no turnover of hardware, software, or intellectual property to the Government. However, technology transfer will still occur through the Essess team, working with ESTCP and ERDC-CERL. Furthermore, it is anticipated that ERDC-CERL will publish an ERDC Technical Report and at least one article in the Society of American Military Engineers' (SAME's) The Military Engineer, or other publications with a military engineer audience.

This technology is limited to scanning the street sides of buildings. As a result, for most buildings, four sides of the buildings will not be scanned. Two or three sides are typically scanned depending on the orientation of a building relative to the street. This technology is also limited by the requirement to have a  $\Delta T$  between building interior and exterior ambient temperatures of at least 20 °F, so scanning must occur when nighttime temperatures are below 50 °F. This limits application of this technology to regions where there is at least 1 week of the year in which nighttime temperatures are below 50 °F. Most regions of the United States fall within this boundary condition. Adjustments are made for empty buildings or buildings where there is no internal heating and no way of knowing the internal temperature setpoint (further discussed in the Methodology Appendix D). This technology is somewhat hindered by trees, bushes and other obstructions that might partially obscure a clear view of a building's envelope from the street. However, the automated data processing pipeline developed by Essess to take the scanned data and prepare it for a report format, corrects for these kinds of obstructions in a number of ways that have been tested by Essess.

## 8 Conclusion

This demonstration validated a method of rapidly and cost effectively scanning and analyzing large numbers of building envelopes, quantifying energy losses, and prioritizing energy leaks for cost-effective repairs or improvements. Over 2500 distinct building feature components were identified across various buildings throughout the base. These features were categorized by type and surface temperature to provide an in-depth look at the energy efficiency of each building's envelope. A quantified analysis showed that Camp Lejeune could save over \$100,000 per year by implementing ECMs outlined in this report. The total investment would be less than \$1 million, but would allow the base to save nearly \$1.7 million over the lifetime of the measures with a simple payback period of less than 9 years.

This work also concludes that Facilities Engineers at other DoD installations can use this demonstrated method to cost effectively evaluate large portions of their building stock to determine the overall condition of their building envelopes and identify opportunities to repair or improve the envelopes to reduce unnecessary energy losses and improve overall energy efficiency. The demonstrated technology offers one avenue to help the DoD reach its goal of saving energy across all military installations by identifying the best candidate installations for energy-saving improvements to building envelopes, i.e., those with the highest potential savings. It would then be possible to combine that priority list with information on optimal building stocks and portfolios of cost-effective improvements to equip the DoD to save millions of dollars in energy loss.

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## **Appendix A: Health and Safety Plan (HASP)**

Since this work requires a vehicle to drive around the installations at low speeds, the Health and Safety Plan mostly entails obeying installation traffic rules. Since the scanning vehicle will be operating at very low speeds, drivers should be careful to avoid blocking faster traffic on higher speed installation roadways. Vehicle lighting systems must be maintained in good working order. The driver(s) must take care to signal all turns and to park outside of the lane of traffic when stopping is necessary.



## Appendix B: Points of Contact

Point of Contact	Organization	Phone & E-mail	Role in Project
James Miller	U.S. Army ERDC-CERL	(217) 373-4566, <a href="mailto:james.p.miller@usace.army.mil">james.p.miller@usace.army.mil</a>	Principal Investigator, COR
Navi Singh	Essess	(857) 445-4135 <a href="mailto:Navi@essess.com">Navi@essess.com</a>	Team Leader
Thomas Burton	USMC, Camp Lejeune, Facilities Engineers	910-451-0784 <a href="mailto:thomas.h.burton@usmc.mil">thomas.h.burton@usmc.mil</a>	Energy Manager

## **Appendix C: Examination of Building Components at Marine Corps Base Camp Lejeune, NC**

This appendix examines specific found in buildings around Marine Corps Base Camp Lejeune, NC, including window frames, door frames, window glass, brick walls, other walls, and soffits (generally speaking, where the wall meets the roof). These components are examined in detail below, as they are all readily remediable through air sealing and insulation improvements.

### **C.1 Building window frames**

Window frames and window glass were differentiated in the 131 buildings on the base that were analyzed in detail to separate out energy loss due to conduction (e.g., poorly insulated single pane windows) and convection (leaks through cracks around window frames, e.g., Figure C-1). The system tagged 1,037 discrete window frames. The measure of leakage is expressed in cubic feet per minute per linear foot of crack. Figure C-2 shows the distribution of estimated leakages across the base.

Figure C-1. Examples of window frame leaks, Camp Lejeune.

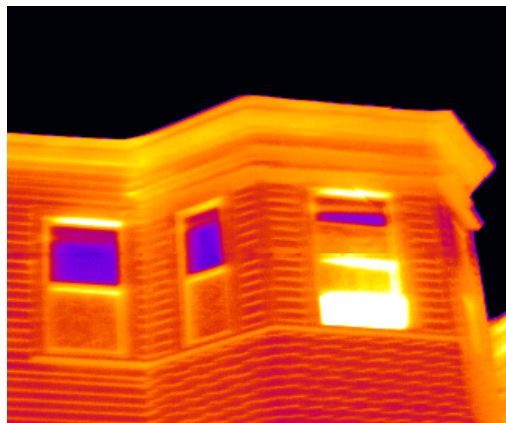
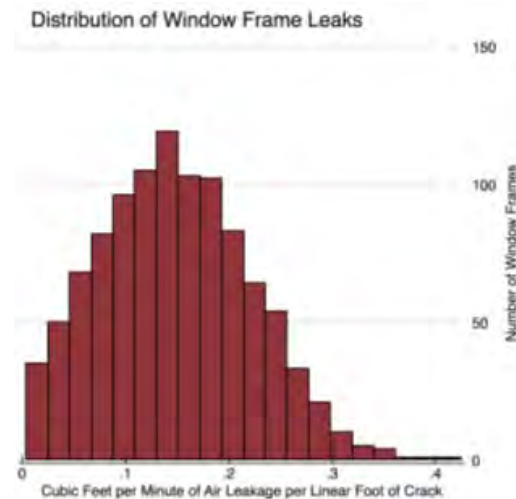
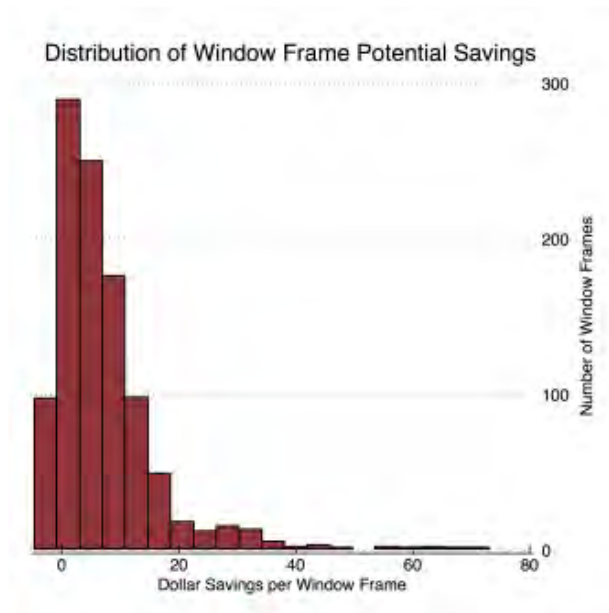


Figure C-2. Distribution of window frame leaks, Camp Lejeune.



Both heating and cooling loss can be calculated once the leakage rate is estimated. Figure C-3 shows the potential remediation savings for each surveyed window. The majority of windows have a savings potential below \$20 per year, with a long tail of potentially very leaky window frames. The leakiest window frames have annual savings potentials through air sealing remediation of nearly \$75 per year. The leakiest window frames identified on the base were in Bldgs 1, 100, 11, 113, 116, and 117.

Figure C-3. Distribution of potential annual energy cost savings due to repair of window frame leaks, Camp Lejeune.



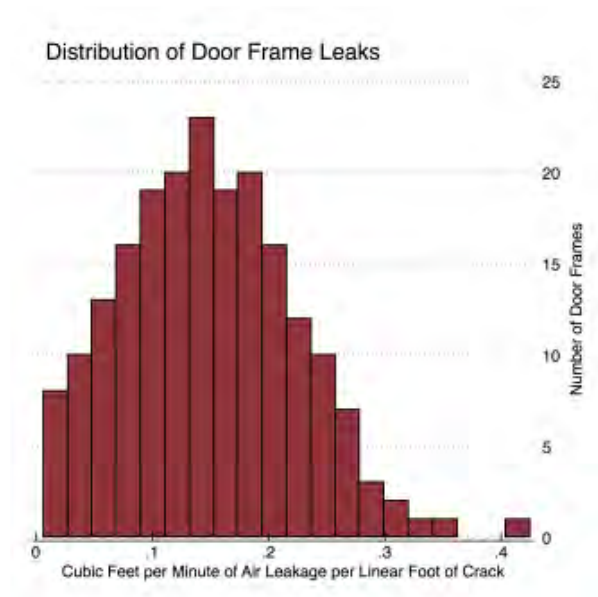
## C.2 Building door frames

Building door frame leakage is estimated through a similar process as window frame leakage by isolating the frame polygon from the door polygon and measuring the emissivity relative to other doors on the base (Figure C-4). There were 201 distinct door frames identified in the buildings analyzed on the base, with a range of leakage from effectively nothing to at or above 0.3 CFM per linear crack foot (Figure C-5).

Figure C-4. Example of door frame energy leaks, Camp Lejeune.

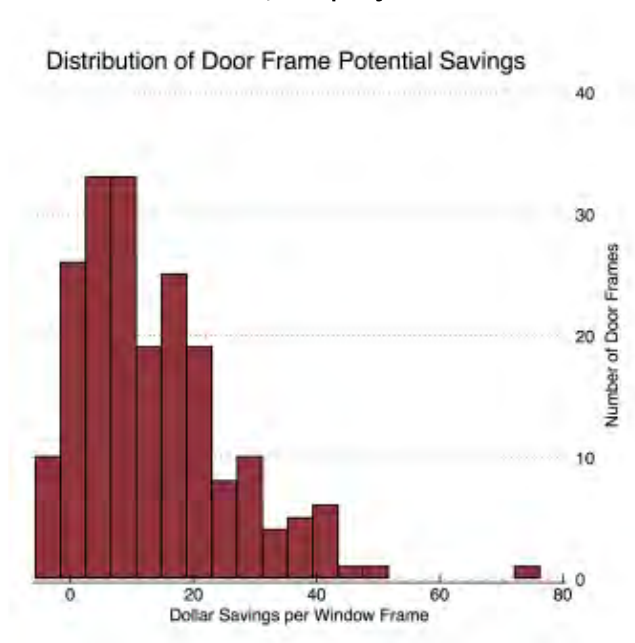


Figure C-5. Distribution of door frame energy leaks, Camp Lejeune.



A distribution of potential annual energy costs savings from remediation of door frame leaks are estimated to range from \$0 to greater than \$50 per year per door frame for some extreme cases (Figure C-6). The average savings potential is about \$20 per door, and remediation through the use of weather-stripping and similar measures is expected to be cost-effective for most doors surveyed on the base. The leakiest door frames identified on the base were in Bldgs 895, 1, HP104, 1688, 20, and 201.

Figure C-6. Distribution of potential annual energy cost savings due to repair of door frame leaks, Camp Lejeune.



### C.3 Walls

Walls on the base were categorized as either brick, siding or concrete. The system identified 315 distinct brick wall polygons, 84 siding walls, and 13 concrete walls. Costs associated with wall polygons were estimated based on their time-normalized surface temperatures (Figure C-7) and inferred R-values, as described in Section 4.2 (“Baseline Characterization”). Estimated annual combined heating and cooling costs from wall polygons range from \$1.40/sq ft to \$3.70/sq ft (Figure C-8). Brick walls in general had lower estimated costs per square foot (~\$1.90) than did siding or concrete walls (~\$2.70).

Figure C-7. Example of thermal energy losses in walls, Camp Lejeune.

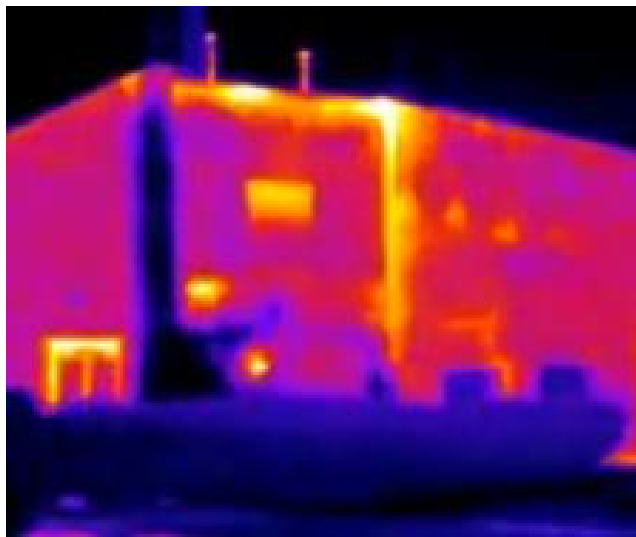
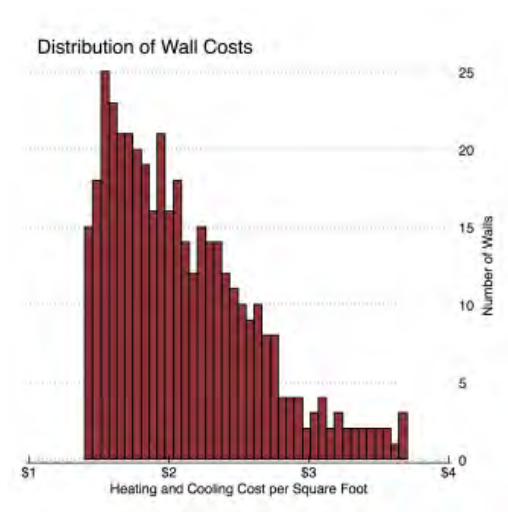


Figure C-8. Distribution of annual energy loss costs per square foot of wall area, Camp Lejeune.

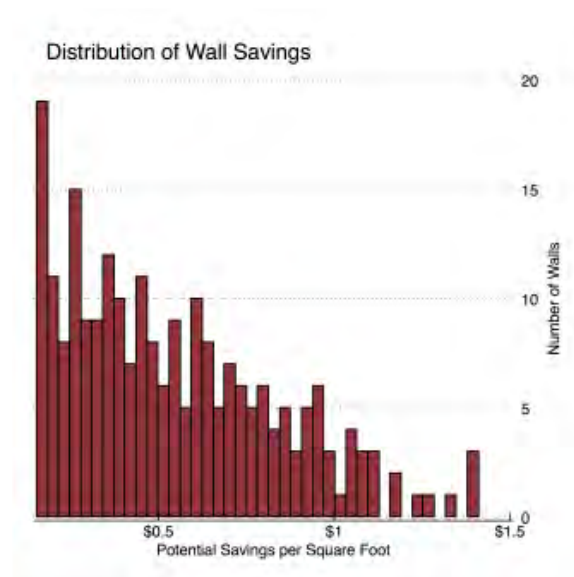


Potential remediation savings for walls were estimated by running the heat flow model on estimated current R-values and post-remediation R-values. Savings range from zero (or negative savings in a few cases of very well insulated walls) up to slightly over \$1.40/sq ft Figure C-9. At an average installation and labor cost of around \$7/sq ft, walls with particularly high energy leakage are cost-effective to remediate.

Of the 412 wall polygons identified, 291 would have positive savings through improved insulation. Of these, approximately 113 would have a payback period of less than 15 years. The average savings associated with improving wall insulation for these 113 cases was around \$0.80/sq ft. The

most emissive walls identified on the base were in Bldgs 2812, 2811, 2900, 2901, H65, and H63.

Figure C-9. Distribution of potential annual energy cost savings due to wall insulation repairs, Camp Lejeune.



## C.4 Roofs

Roof heat loss is calculated similarly to wall heat loss, by looking at time-normalized surface temperatures (Figure C-10). The system identified 232 distinct roof polygons. (Note that a single roof will usually have more than one polygon identified, as the maximum size of a polygon is dictated by the FOV of the camera in a single image frame.) The estimated heating and cooling cost associated with these roofs ranged from \$1.10 to \$2.20/sq ft. A distribution of annual energy loss costs per square foot of roof area (Figure C-11).

Figure C-10. Example of thermal energy losses in roofs, Camp Lejeune.

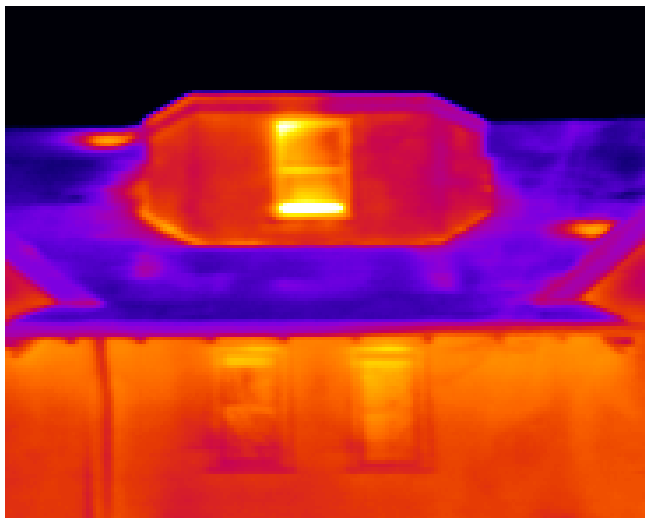
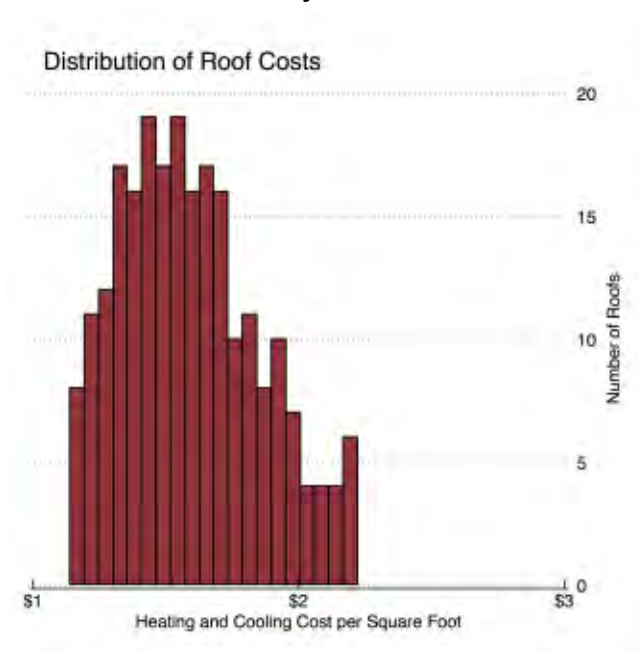


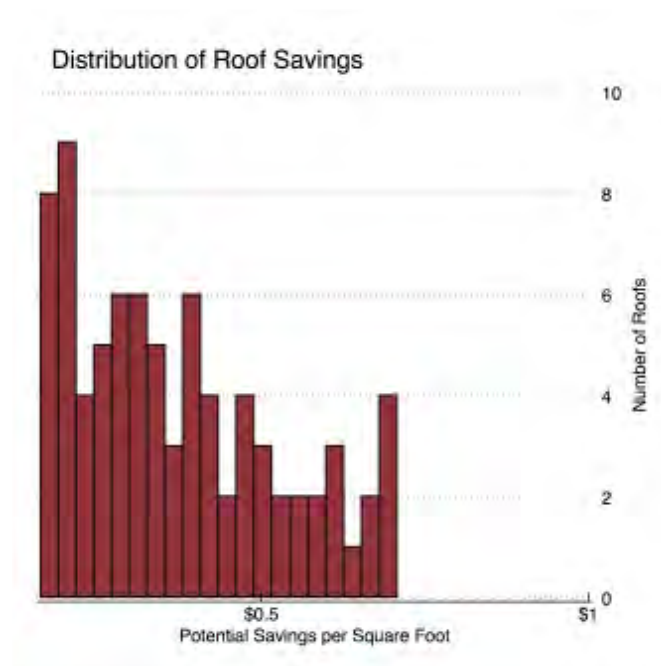
Figure C-11. Distribution of annual energy loss costs per square foot of roof area, Camp Lejeune.



Of the 133 roof polygons identified that had positive remediation savings, 14 had paybacks of less than 15 years. The average savings associated with improving roof insulation for these 14 cases was around \$0.60/sq ft (Figure C-12). The most emissive roofs identified on the base were on Bldgs 2900, HP328, 1984, 2901, 504, and 430.



Figure C-12. Potential annual energy cost savings per square foot due to roof insulation repairs, Camp Lejeune.



## C.5 Soffits

Soffits are areas where the wall meets the roof and are often spots where insulation is poor and air leaks are more common. The system identified 329 total soffit polygons on buildings in the base. Their R-values were estimated based on surface temperatures (Figure C-13) similar to the calculation for walls and roofs. The average annual heating and cooling costs for soffits range from \$1.40 to \$2.80/sq ft (Figure C-14).

Figure C-13. Example of a leaky soffit, Camp Lejeune.

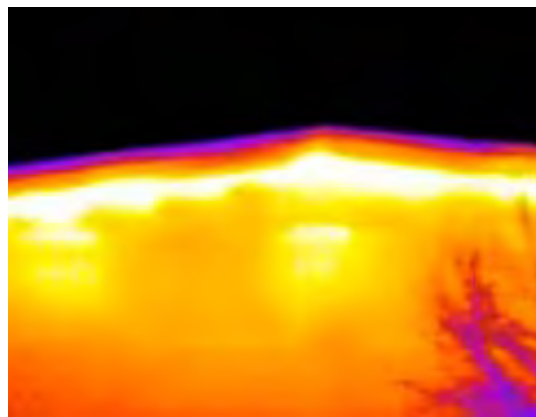
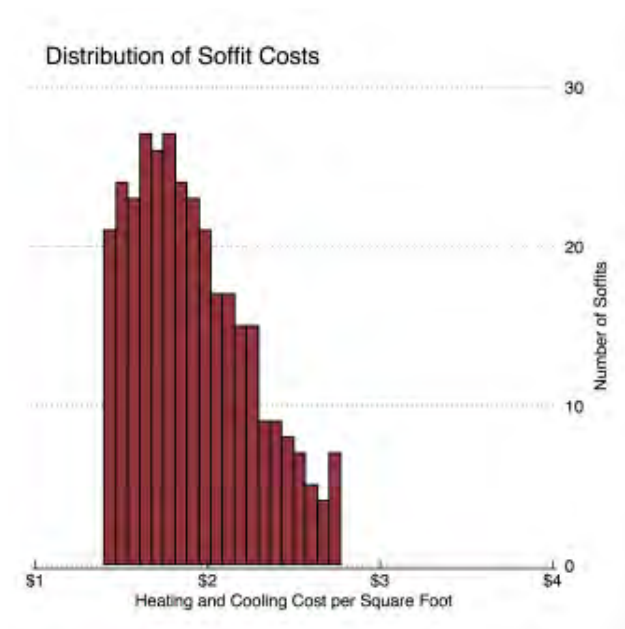
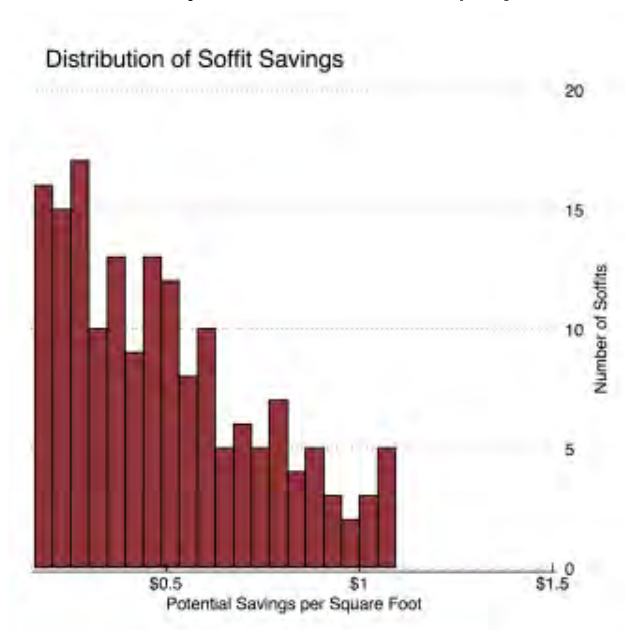


Figure C-14. Distribution of annual energy costs due to thermally inefficient soffits, Camp Lejeune.



Of the 229 soffit polygons that had positive remediation savings, 64 had paybacks of less than 15 years. The average savings associated with improving soffit insulation for these 64 cases was around \$0.80/sq ft (Figure C-15). The most emissive soffits identified on the base were on Bldgs 1206, HP210, 319, 2900, 2901, and 302.

Figure C-15. Distribution of potential annual energy cost savings due to repair of thermally inefficient soffits, Camp Lejeune.



## Appendix D: Thirty Building Detailed Analysis for Marine Corps Base Camp Lejeune, NC

### D.1 Bldg 1

#### D.1.1 Description of Bldg 1, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 36,832

**Avg. Daily Electric Use:** 2,166 kWh

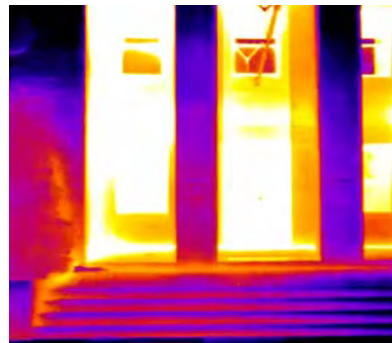
**Electricity Score:** 80<sup>th</sup> Percentile

Bldg 1 (Figure D-1 and D-2) has an electricity usage of 21.5 kWh/sq ft/yr.

Figure D-1. Aerial view of Bldg 1, Camp Lejeune.



Figure D-2. Thermal image of Bldg 1, Camp Lejeune.



#### D.1.2 Notable leaks at Bldg 1, Marine Corps Base Camp Lejeune, NC

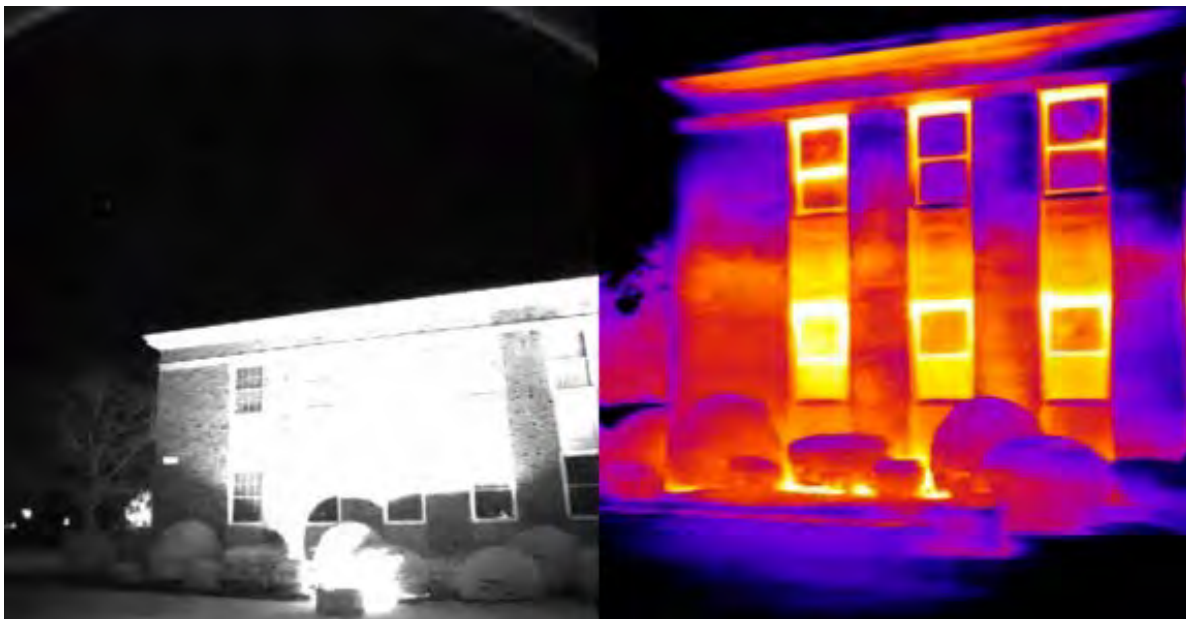
The brick wall at timestamp 323:17 in the online drive-by application is highly emissive (Figure D-3). There are some insulation holes around the middle of the wall, and the overall surface appears poorly insulated compared to other walls on the base.

Figure D-3. NIR image (left) and thermal image (right) of Bldg 1, Camp Lejeune.



The wall at timestamp 323:22 is also highly emissive, and has some apparent insulation holes near the middle of the wall (Figure D-4). The soffit is also fairly emissive, and the window frames in the upper left are potentially leaky.

Figure D-4. NIR image (left) and thermal image (right) of Bldg 1, Camp Lejeune. Note apparent insulation holes near the middle of the wall, a fairly emissive soffit and apparently leaky window frames.



### D.1.3 Envelope ECMs for Bldg 1, Marine Corps Base Camp Lejeune, NC

Figure D-5 shows the relative ROI for envelope ECMs for Bldg 1, Camp Lejeune.

Figure D-5. ECM profile for Bldg 1, Camp Lejeune.

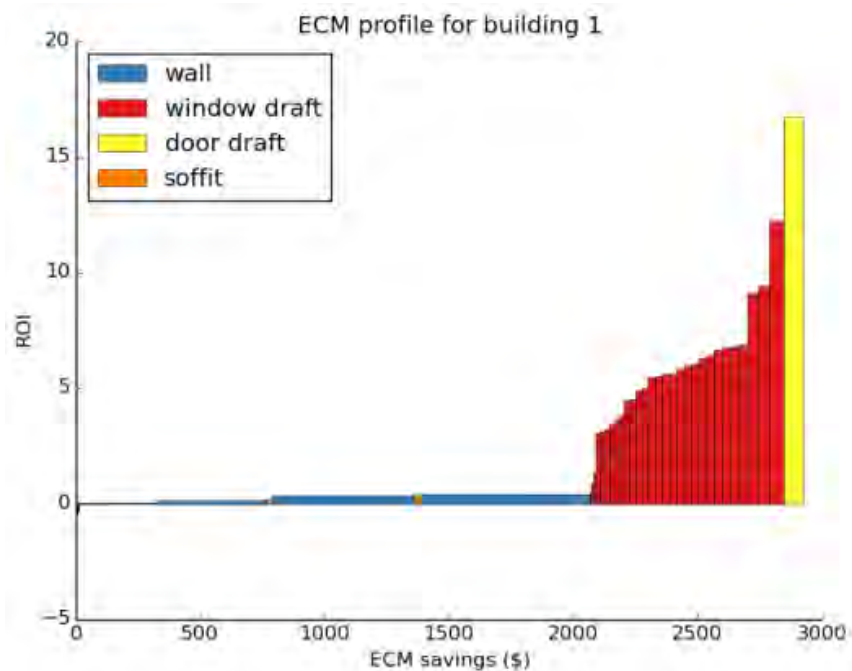


Table D-1 lists the recommended envelope ECMs for Bldg 1, Camp Lejeune

Table D-1. Envelope ECMs for Bldg 1, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	3161	3096	2003	24240	12.1
Seal Window Frame Leaks	1244	1218	788	2069	2.6
Seal Door Frame Leaks	120	118	76	65	0.8
Improve Soffit Insulation	79	77	50	583	11.7

Annual potential remediation savings for this building are \$2,918 and total payback is 9.2 years for envelope-related ECMs.

## D.2 Bldg 8

### D.2.1 Description of Bldg 8, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 26,602

**Avg. Daily Electric Use:** 1,517 kWh

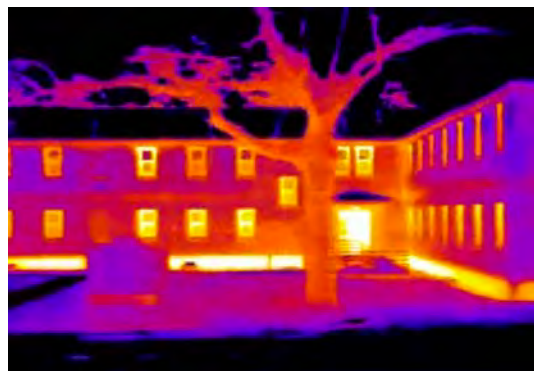
**Electricity Score:** 95<sup>th</sup> Percentile

Bldg 8 (Figures D-6 and D-7) has an electricity usage of 20.8 kWh/sq ft/yr.

Figure D-6. Aerial view of Bldg 8, Camp Lejeune.



Figure D-7. Thermal image of Bldg 8, Camp Lejeune.



### D.2.2 Notable leaks at Bldg 8, Marine Corps Base Camp Lejeune, NC

The wall of Bldg 8 at timestamp 319:57 is highly emissive relative to other buildings on the base (Figure D-8). The exposed foundation wall is also poorly insulated, allowing heat to escape from the surface. The window frames on the left side of the building are highly emissive.



Figure D-8. NIR image (left) and thermal image (right) of Bldg 8, Camp Lejeune.



The wall at timestamp 319:58 is quite emissive, with a notable thermal bridge around the middle of the wall (Figure D-9).

Figure D-9. NIR image (left) and thermal image (right) of Bldg 8, Camp Lejeune. Note the thermal bridge around the middle of the wall.



### D.2.3 Envelope ECMs for Bldg 8, Marine Corps Base Camp Lejeune, NC

Figure D-10 shows the relative ROI for envelope ECMs for Bldg 8, Camp Lejeune.

Figure D-10. ECM profile for Bldg 8, Camp Lejeune.

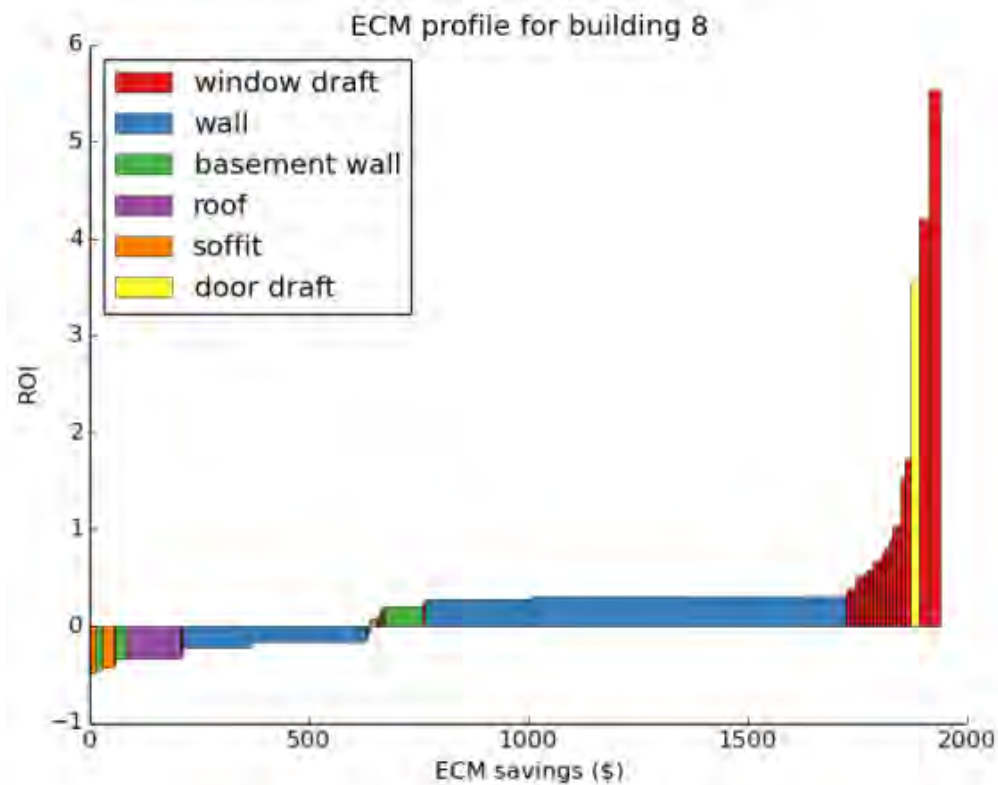


Table D-2 lists the recommended envelope ECMs for Bldg 8, Camp Lejeune.

Table D-2. Envelope ECMs for Bldg 8, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	2168	2123	1374	18682	13.6
Seal Window Frame Leaks	372	364	236	2005	8.5
Basement Wall Insulation	232	227	147	2334	15.9
Improve Roof Insulation	192	188	122	2749	22.5
Improve Soffit Insulation	67	66	42	1144	26.9

Annual potential remediation savings for this building are \$1,941 and total payback is 13.9 years for envelope-related ECMs.



## D.3 Bldg 11

### D.3.1 Description of Bldg 11, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 3,998

**Avg. Daily Electric Use:** Not Provided

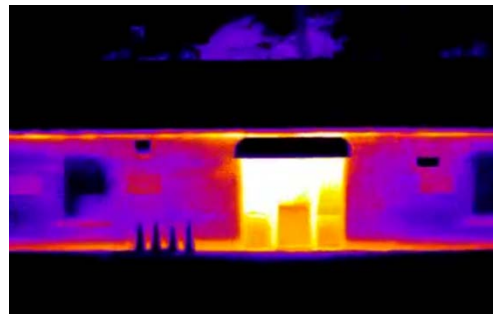
**Electricity Score:** N/A

Figures D-11 and D-12, respectively, show the aerial view and thermal image of Bldg 11, Camp Lejeune.

Figure D-11. Aerial view of Bldg 11, Camp Lejeune.



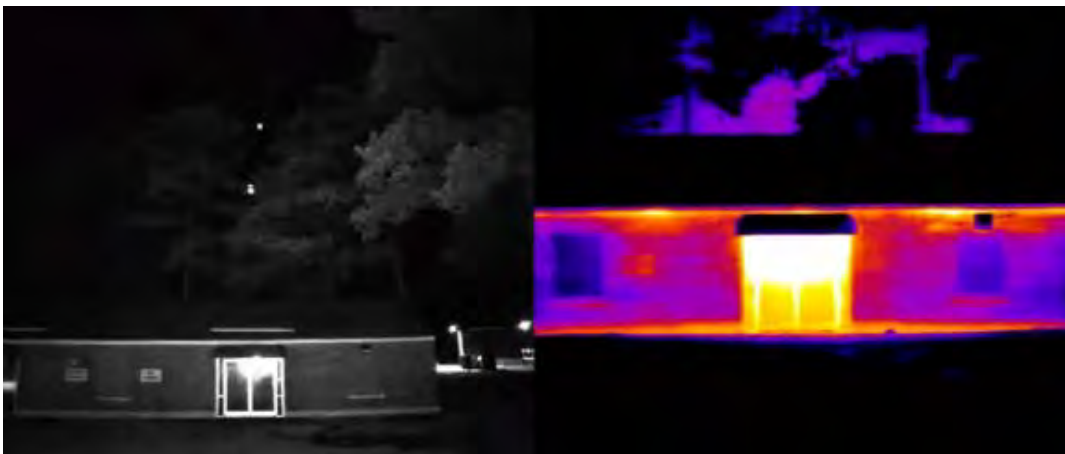
Figure D-12. Thermal image of Bldg 11, Camp Lejeune.



### D.3.2 Notable leaks at Bldg 11, Marine Corps Base Camp Lejeune, NC

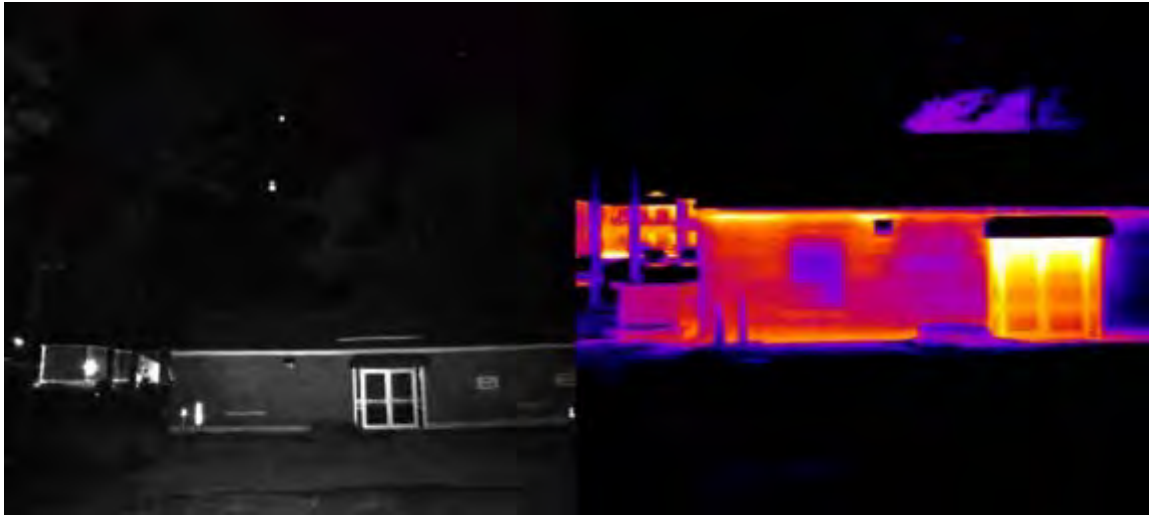
The soffit at timestamp 322:04 and the door frame are highly emissive, which potentially indicates poor insulation or convective leaks (Figure D-13). There are two notable hot spots to the left and right of the door.

Figure D-13. NIR image (left) and thermal image (right) of Bldg 11, Camp Lejeune.



The wall to the left of the door at timestamp 322:07 has a number of emissive hot spots, as well as an emissive soffit (Figure D-14).

Figure D-14. NIR image (left) and thermal image (right) of Bldg 11, Camp Lejeune. The wall to the left of the door has a number of emissive hot spots, as well as an emissive soffit.



### D.3.3 Envelope ECMs for Bldg 11, Marine Corps Base Camp Lejeune, NC

Figure D-15 shows the relative ROI for envelope ECMs for Bldg 11, Camp Lejeune.

Figure D-15. ECM profile for Bldg 11, Camp Lejeune.

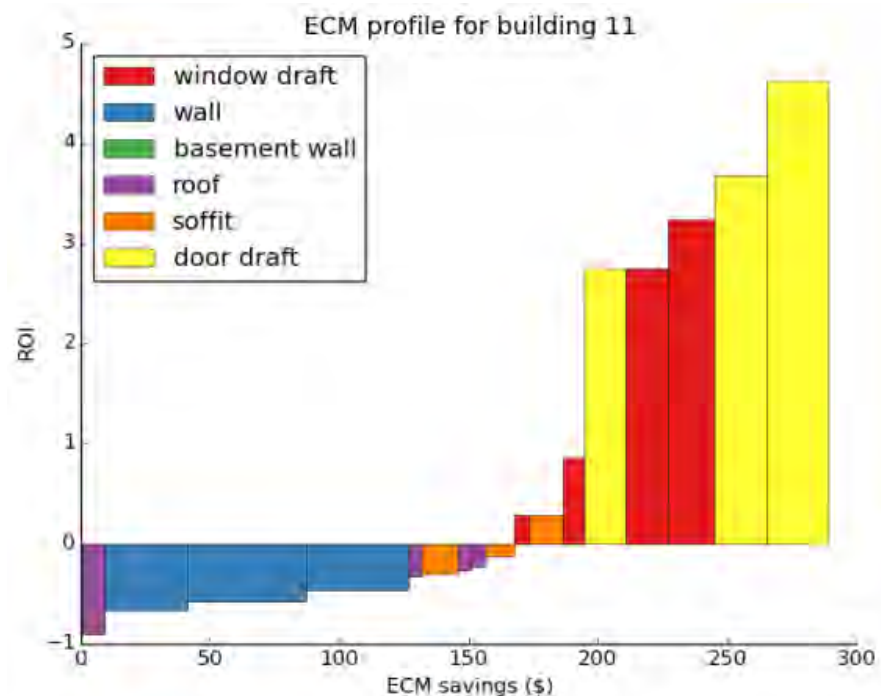


Table D-3 lists the recommended envelope ECMs for Bldg 11, Camp Lejeune.

Table D-3. Envelope ECMs for Bldg 11, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Door Frame Leaks	95	93	60	193	3.2
Seal Window Frame Leaks	76	74	48	260	5.4
Improve Wall Insulation	62	61	40	1123	28.4
Improve Soffit Insulation	61	60	39	661	17.0
Improve Roof Insulation	24	24	15	317	20.8

Annual potential remediation savings for this building are \$202 and total payback is 12.6 years for envelope-related ECMs.

## D.4 Bldg 15

### D.4.1 Description of Bldg 15, Marine Corps Base Camp Lejeune, NC

**Name:** Medical/Dental Clinic

**Use Type:** Health

**Square Footage:** 18,222

**Avg. Daily Electric Use:** Not Provided

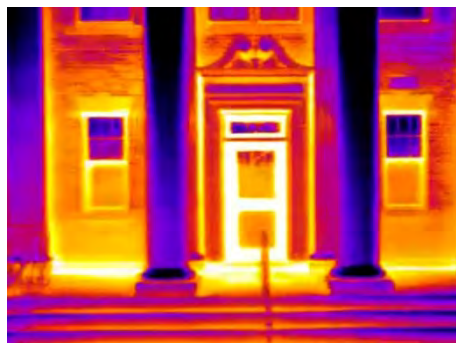
**Electricity Score:** N/A

Figures D-16 and D-17, respectively, show the aerial view and thermal image of Bldg 15, Camp Lejeune.

Figure D-16. Aerial view of Bldg 15, Camp Lejeune.



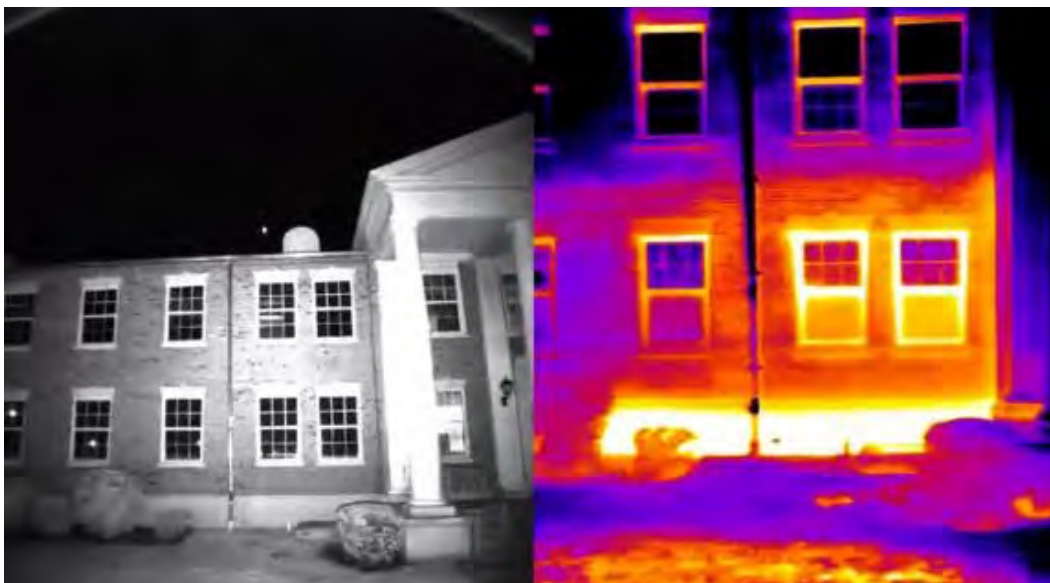
Figure D-17. Thermal image of Bldg 15, Camp Lejeune.



#### D.4.2 Notable leaks at Bldg 15, Marine Corps Base Camp Lejeune, NC

The wall and exposed foundation of Bldg 15 at timestamp 324:17 are quite emissive, which indicates poor insulation (Figure D-18). The two window frames in the bottom right corner are notably hot, and may have high convective air leakage.

Figure D-18. NIR image (left) and thermal image (right) of Bldg 15, Camp Lejeune.



#### D.4.3 Envelope ECMs for Bldg 15, Marine Corps Base Camp Lejeune, NC

Figure D-19 shows the relative ROI for envelope ECMs for Bldg 15, Camp Lejeune.

Figure D-19. ECM profile for Bldg 15, Camp Lejeune.

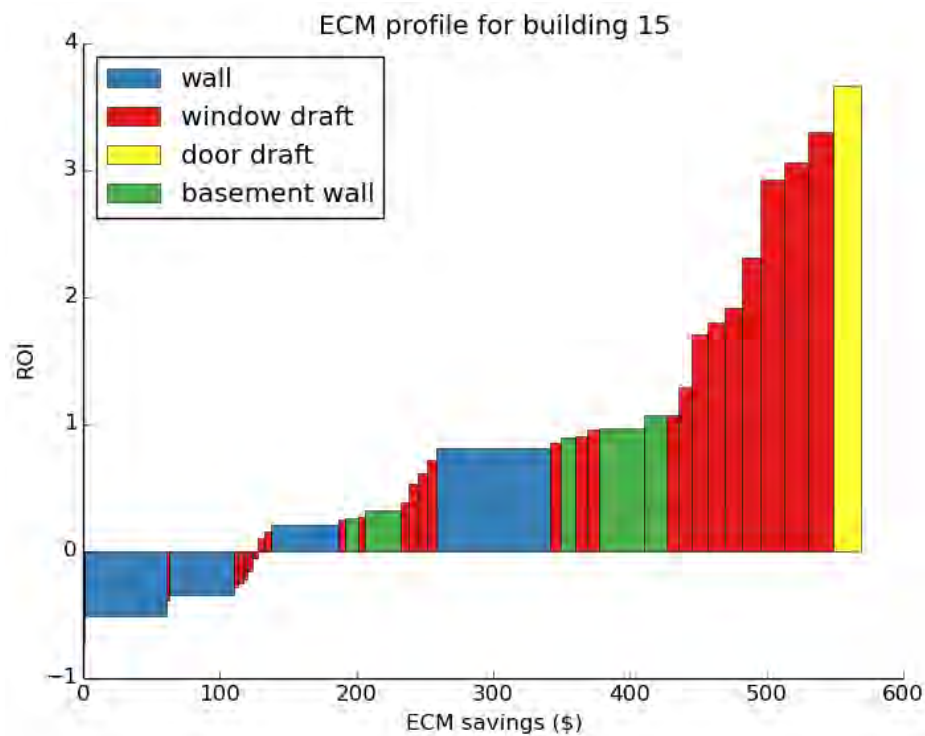


Table D-4 lists the recommended envelope ECMs for Bldg 15, Camp Lejeune.

Table D-4. Envelope ECMs for Bldg 15, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Window Frame Leaks	338	331	214	1681	7.9
Improve Wall Insulation	282	276	179	2382	13.3
Basement Wall Insulation	150	147	95	860	9.0
Seal Door Frame Leaks	32	31	20	65	3.2

Annual potential remediation savings for this building are \$508 and total payback is 9.8 years for envelope-related ECMs.



## D.5 Bldg 18

### D.5.1 Description of Bldg 18, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Misc.

**Square Footage:** 13,122

**Avg. Daily Electric Use:** 560.7 kWh

**Electricity Score:** 65<sup>th</sup> Percentile

Bldg 18 (Figures D-20 and D-21) has an electricity usage of 15.6 kWh/sq ft/yr.

Figure D-20. Aerial view of Bldg 18, Camp Lejeune.



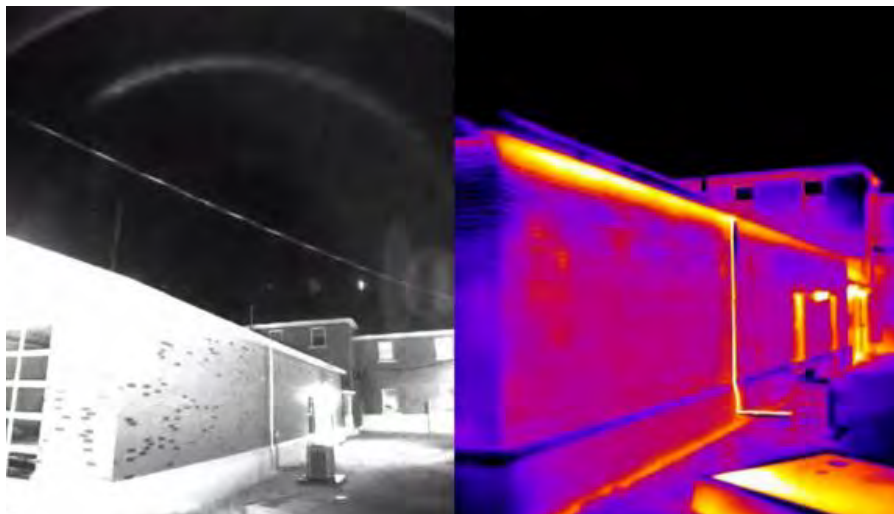
Figure D-21. Thermal image of Bldg 18, Camp Lejeune.



### D.5.2 Notable leaks at Bldg 18, Marine Corps Base Camp Lejeune, NC

The soffit on Bldg 18 at timestamp 91:18 is highly emissive. There is also a small hot spot on the wall on the left side of the image (Figure D-22).

Figure D-22. NIR image (left) and thermal image (right) of Bldg 18, Camp Lejeune.



The wall near the center of the building at timestamp 91:23 and the exposed foundation/basement wall are highly emissive, which indicates poor insulation (Figure D-23).

Figure D-23. NIR image (left) and thermal image (right) of Bldg 18, Camp Lejeune. The wall near the center of the building and the exposed foundation/basement wall are highly emissive.



### D.5.3 Envelope ECMs for Bldg 18, Marine Corps Base Camp Lejeune, NC

Figure D-24 shows the relative ROI for envelope ECMs for Bldg 18, Camp Lejeune.

**Figure D-24. ECM profile for Bldg 18, Camp Lejeune.**

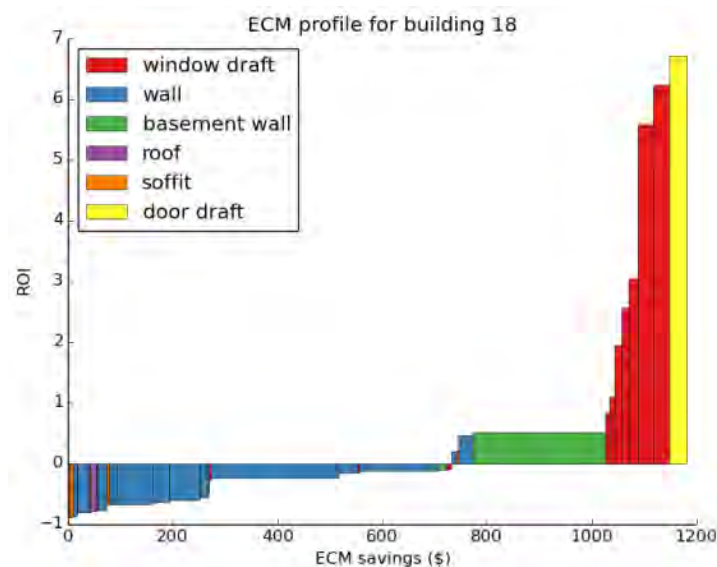


Table D-5 lists the recommended envelope ECMs for Bldg 18, Camp Lejeune.

Table D-5. Envelope ECMs for Bldg 18, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	740	724	468	8456	18.0
Basement Wall Insulation	427	418	271	2801	10.4
Seal Window Frame Leaks	216	211	137	713	5.2
Seal Door Frame Leaks	52	51	33	64	1.9

Annual potential remediation savings for this building are \$909 and total payback is 13.2 years for envelope-related ECMs.

## D.6 Bldg 20

### D.6.1 Description of Bldg 20, Marine Corps Base Camp Lejeune, NC

**Name:** Industrial Facility

**Use Type:** Misc.

**Square Footage:** 10,690

**Avg. Daily Electric Use:** Not Provided

**Electricity Score:** N/A

Figures D-25 and D-26, respectively, show the aerial view and thermal image of Bldg 15, Camp Lejeune.

Figure D-25. Aerial view of Bldg 20, Camp Lejeune.

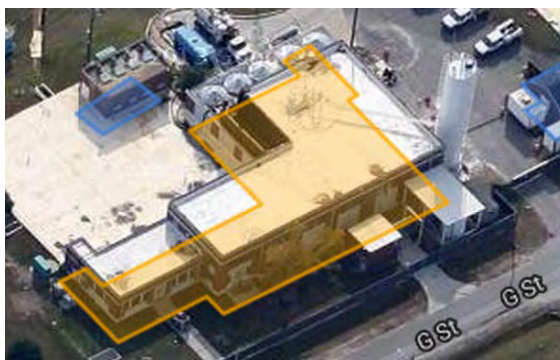
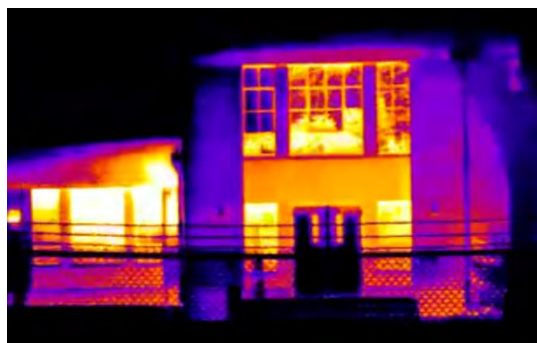


Figure D-26. Thermal image of Bldg 20, Camp Lejeune.

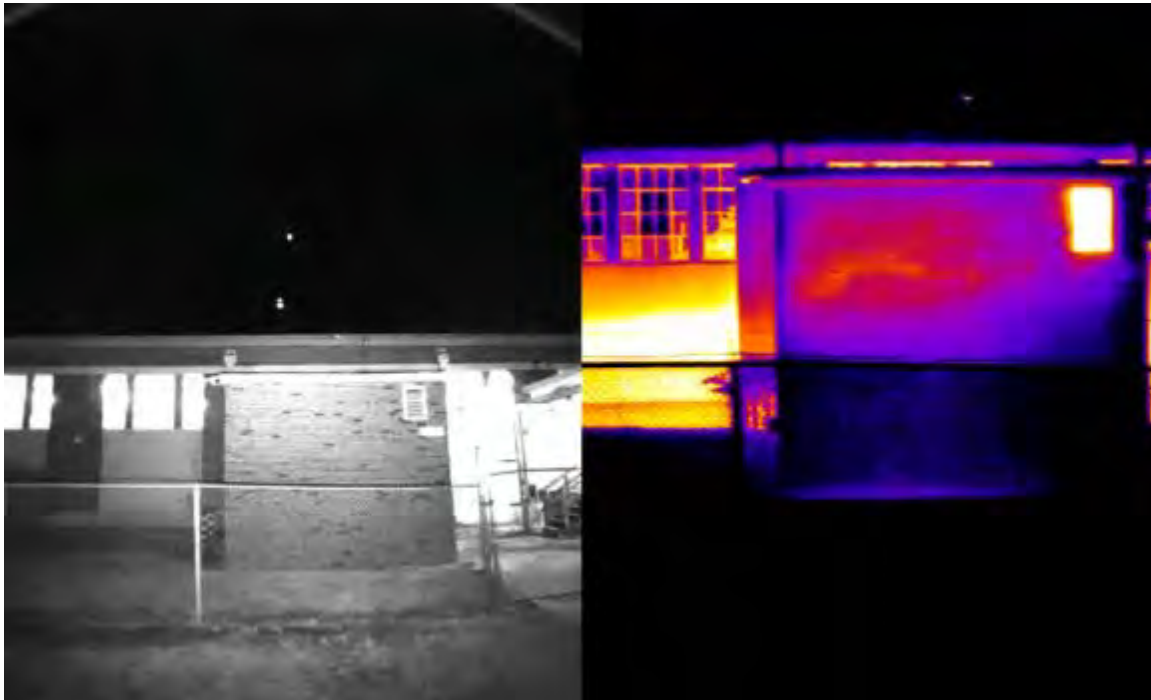


### D.6.2 Notable leaks at Bldg 20, Marine Corps Base Camp Lejeune, NC

There is a hot spot on the middle of the wall of Bldg 20 at timestamp 313:13 that may indicate a hole in the wall insulation (Figure D-27).

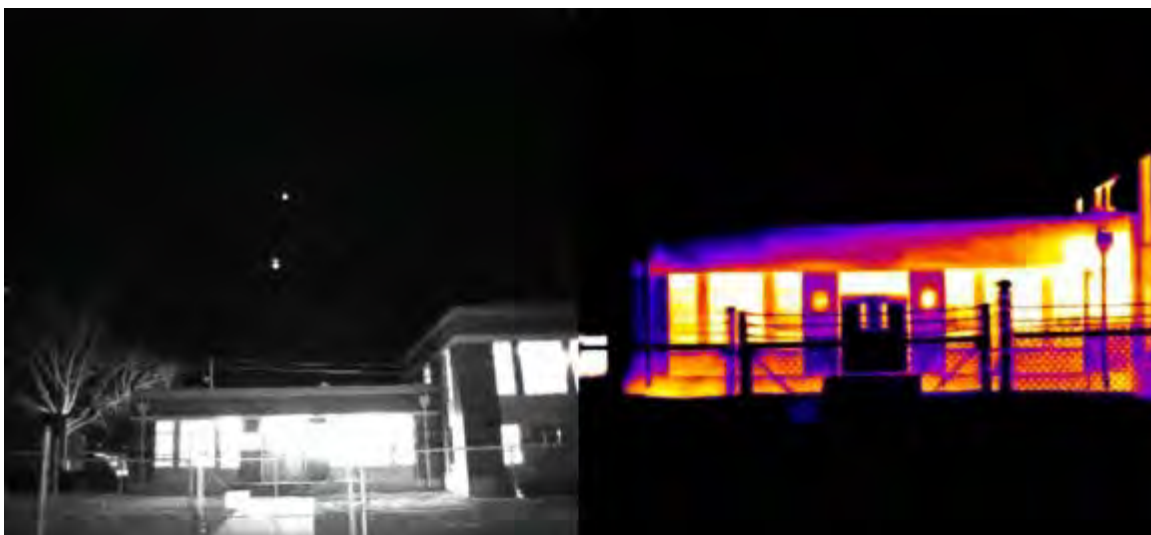


Figure D-27. NIR image (left) and thermal image (right) of Bldg 20, Camp Lejeune.



The windows visible at timestamp 313:16 are notably emissive. There are also some leaks along the door in the center of the image (Figure D-28).

Figure D-28. NIR image (left) and thermal image (right) of Bldg 20, Camp Lejeune. The windows are notably emissive and there are leaks along the door in the center of the image.



### D.6.3 Envelope ECMs for Bldg 20, Marine Corps Base Camp Lejeune, NC

Figure D-29 shows the relative ROI for envelope ECMs for Bldg 20, Camp Lejeune.

Figure D-29. ECM profile for Bldg 20, Camp Lejeune.

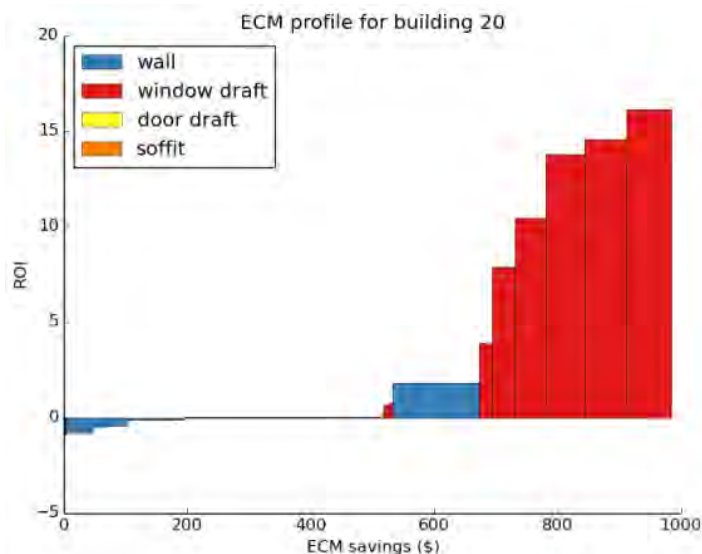


Table D-6 lists the recommended envelope ECMs for Bldg 20, Camp Lejeune.

Table D-6. Envelope ECMs for Bldg 20, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	916	897	581	7958	13.7
Seal Window Frame Leaks	516	506	327	517	1.6

Annual potential remediation savings for this building are \$908 and total payback is 9.3 years for envelope-related ECMs.

## D.7 Bldg 26

### D.7.1 Description of Bldg 26, Marine Corps Base Camp Lejeune, NC

**Name:** Training Material Storage

**Use Type:** Misc.

**Square Footage:** 3,553

**Avg. Daily Electric Use:** Not Provided

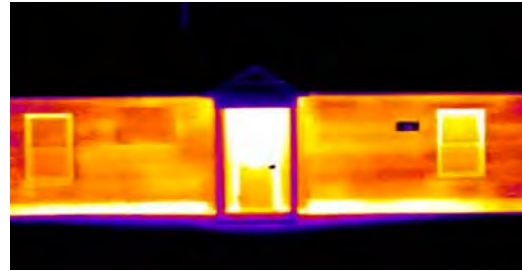
**Electricity Score:** N/A

Figures D-30 and D-31, respectively, show the aerial view and thermal image of Bldg 26, Camp Lejeune.

Figure D-30. Aerial view of Bldg 26, Camp Lejeune.



Figure D-31. Thermal image of Bldg 26, Camp Lejeune.



### D.7.2 Notable leaks at Bldg 26, Marine Corps Base Camp Lejeune, NC

The wall of Bldg 26 visible at timestamp 321:34 had particularly poor insulation, with large notable hotspots (Figure D-32). The door in the center has large leaks in the frame that could potentially be mitigated through air sealing.

Figure D-32. NIR image (left) and thermal image (right) of Bldg 26, Camp Lejeune.



### D.7.3 Envelope ECMs for Bldg 26, Marine Corps Base Camp Lejeune, NC

Figure D-33 shows the relative ROI for envelope ECMs for Bldg 26, Camp Lejeune.

Figure D-33. ECM profile for Bldg 26, Camp Lejeune.

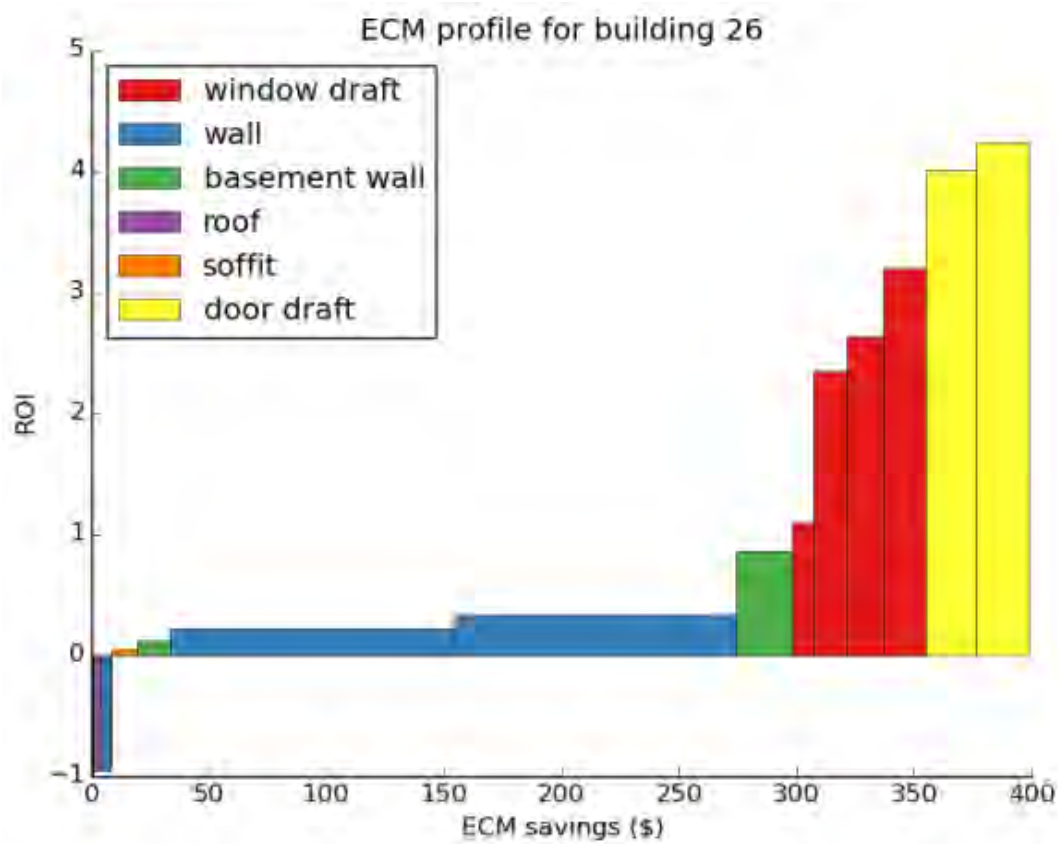


Table D-7 lists the recommended envelope ECMs for Bldg 26, Camp Lejeune.

Table D-7. Envelope ECMs for Bldg 26, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	379	371	240	2837	11.8
Seal Window Frame Leaks	90	88	57	259	4.5
Seal Door Frame Leaks	69	68	44	129	2.9
Basement Wall Insulation	61	59	38	388	10.1
Improve Soffit Insulation	17	17	11	154	14.4

Annual potential remediation savings for this building are \$390 and total payback is 9.6 years for envelope-related ECMs.

## D.8 Bldg 37

### D.8.1 Description of Bldg 37, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 10,068

**Avg. Daily Electric Use:** 405.5 kWh

**Electricity Score:** 60<sup>th</sup> Percentile

**Electricity Usage:** 14.7 kWh/sq ft/yr.

Figures D-34 and D-35, respectively, show the aerial view and thermal image of Bldg 37, Camp Lejeune.

Figure D-34. Aerial view of Bldg 37, Camp Lejeune.

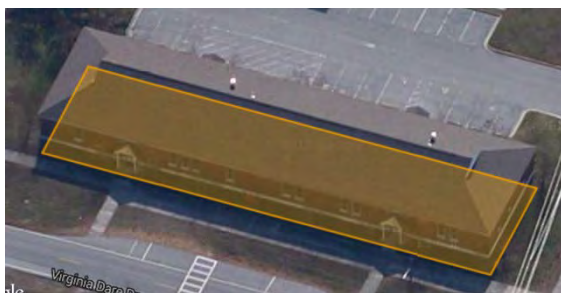
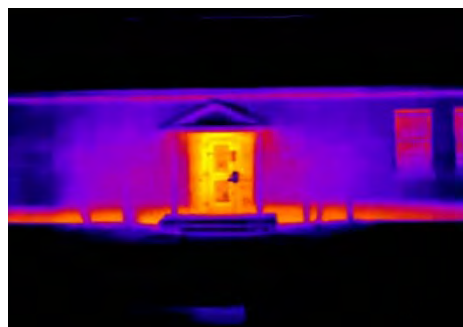


Figure D-35. Thermal image of Bldg 37, Camp Lejeune.



### D.8.2 Notable leaks at Bldg 37, Marine Corps Base Camp Lejeune, NC

The exposed foundation of Bldg 37 at timestamp 133:58 is highly emissive (Figure D-36). The window frames are also much warmer than typical window frames on Lejeune buildings, which indicates convective leakage.

Figure D-36. NIR image (left) and thermal image (right) of Bldg 37, Camp Lejeune.



### D.8.3 Envelope ECMs for Bldg 37, Marine Corps Base Camp Lejeune, NC

Figure D-37 shows the relative ROI for envelope ECMs for Bldg 37, Camp Lejeune.

Figure D-37. ECM profile for Bldg 37, Camp Lejeune.

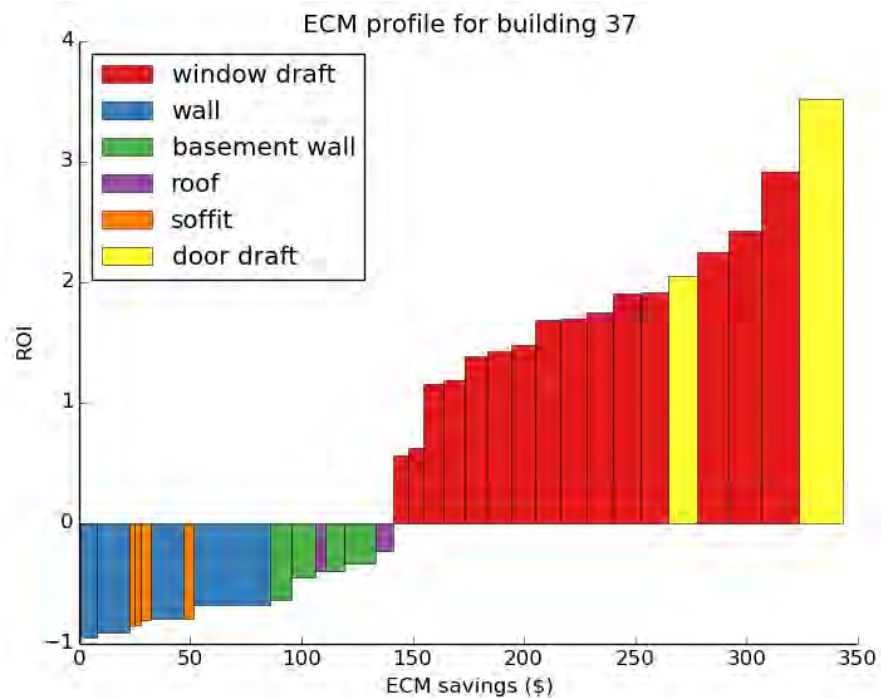


Table D-8 lists the recommended envelope ECMs for Bldg 37, Camp Lejeune.



Table D-8. Envelope ECMs for Bldg 37, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Window Frame Leaks	268	262	170	972	5.7
Basement Wall Insulation	53	51	33	828	24.9
Seal Door Frame Leaks	51	50	32	128	4.0

Annual potential remediation savings for this building are \$247 and total payback is 8.8 years for envelope-related ECMs.

## D.9 Bldg 58

### D.9.1 Description of Bldg 58, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 31,043

**Avg. Daily Electric Use:** 1,898 kWh

**Electricity Score:** 95<sup>th</sup> Percentile

Bldg 58 (Figures D-38 and D-38) has an electricity usage of 22.3 kWh/sq ft/yr.

Figure D-38. Aerial view of Bldg 58, Camp Lejeune.



Figure D-39. Thermal image of Bldg 58, Camp Lejeune.



### D.9.2 Notable leaks at Bldg 58, Marine Corps Base Camp Lejeune, NC

Bldg 58 has a thermal bridge noticeable near the middle of the wall on the right side at timestamp 134:44 (Figure D-40). There is also a hot spot on the wall on the left side of the image.

Figure D-40. NIR image (left) and thermal image (right) of Bldg 58, Camp Lejeune.



There are some leaks near the foundation at timestamp 134:49. The door-frame is also particularly emissive (Figure D-41).

Figure D-41. NIR image (left) and thermal image (right) of Bldg 58, Camp Lejeune. Note leaks near the foundation and at the door frame.



### D.9.3 Envelope ECMs for Bldg 58, Marine Corps Base Camp Lejeune, NC

Figure D-42 shows the relative ROI for envelope ECMs for Bldg 58, Camp Lejeune.



Figure D-42. ECM profile for Bldg 58, Camp Lejeune.

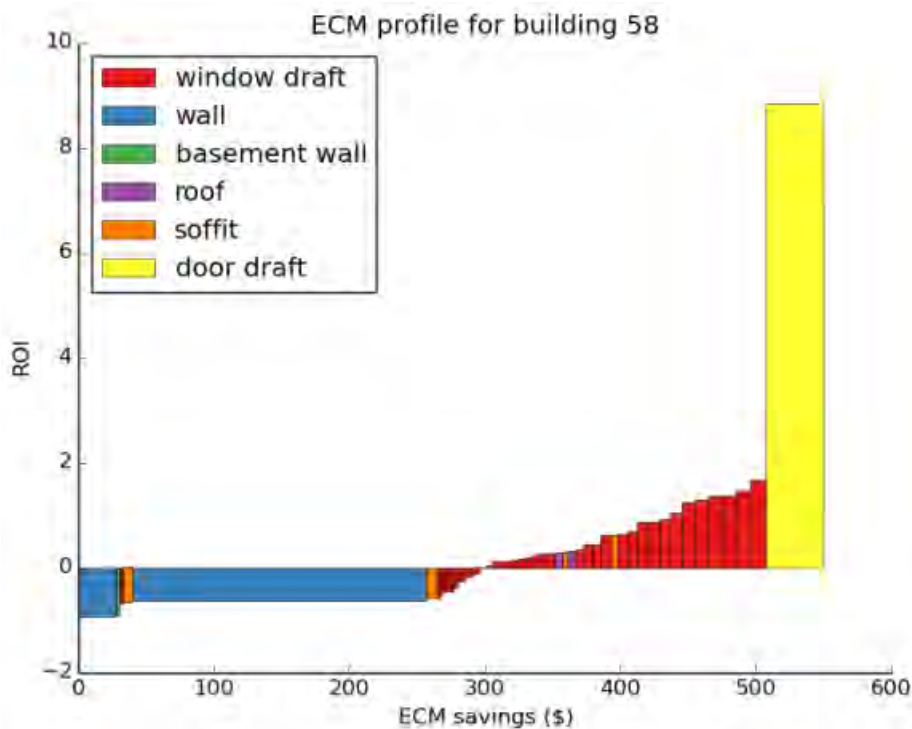


Table D-9 lists the recommended envelope ECMs for Bldg 58, Camp Lejeune.

Table D-9. Envelope ECMs for Bldg 58, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Window Frame Leaks	344	337	218	2392	11.0
Seal Door Frame Leaks	66	65	42	64	1.5
Improve Roof Insulation	19	18	12	136	11.6

Annual potential remediation savings for this building are \$272 and total payback is 9.5 years for envelope-related ECMs.

## D.10 Bldg 62

### D.10.1 Description of Bldg 62, Marine Corps Base Camp Lejeune, NC

**Name:** Recreation Center

**Use Type:** Recreation

**Square Footage:** 16,426

**Avg. Daily Electric Use:** 1,482 kWh

**Electricity Score:** 95<sup>th</sup> Percentile

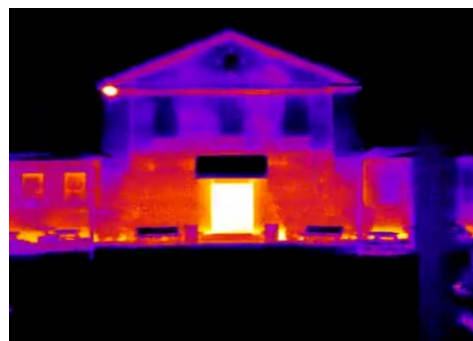
**Electricity Usage:** 32.9 kWh/sq ft/yr

Figures D-43 and D-44, respectively, show the aerial view and thermal image of Bldg 62, Camp Lejeune.

Figure D-43. Aerial view of Bldg 62, Camp Lejeune.



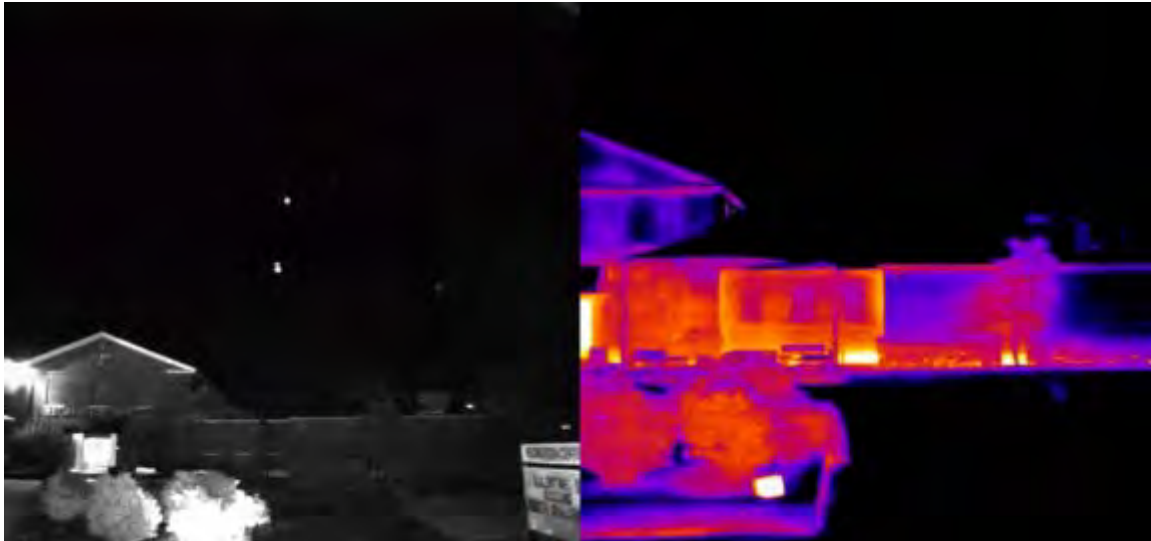
Figure D-44. Thermal image of Bldg 62, Camp Lejeune.



### D.10.2 Notable leaks at Bldg 62, Marine Corps Base Camp Lejeune, NC

The walls of Bldg 62 at timestamp 325:33 are poorly insulated (Figure D-45).

Figure D-45. NIR image (left) and thermal image (right) of Bldg 62, Camp Lejeune.



The soffit at timestamp 325:36 is emissive, as are the window frames visible in the image (Figure D-46).

Figure D-46. NIR image (left) and thermal image (right) of Bldg 62, Camp Lejeune. The soffit and window frames appear to be highly emissive.



### D.10.3 Envelope ECMs for Bldg 62, Marine Corps Base Camp Lejeune, NC

Figure D-47 shows the relative ROI for envelope ECMs for Bldg 62, Camp Lejeune.

Figure D-47. ECM profile for Bldg 62, Camp Lejeune.

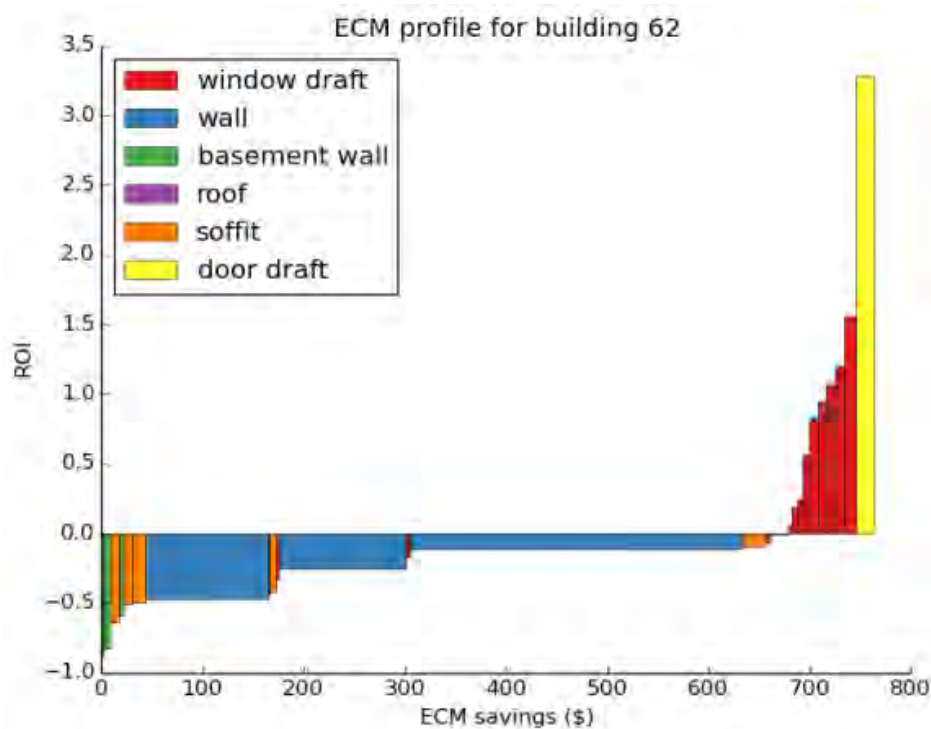


Table D-10 lists the recommended envelope ECMs for Bldg 62, Camp Lejeune.

Table D-10. Envelope ECMs for Bldg 62, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	903	884	572	11474	20.0
Seal Window Frame Leaks	127	124	80	841	10.5
Improve Soffit Insulation	46	45	29	543	18.5
Seal Door Frame Leaks	29	28	18	64	3.5
Improve Roof Insulation	27	27	17	261	15.1

Annual potential remediation savings for this building are \$718 and total payback is 18.4 years for envelope-related ECMs.

## D.11 Bldg 116

### D.11.1 Description of Bldg 116, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 3,688

**Avg. Daily Electric Use:** Not Provided

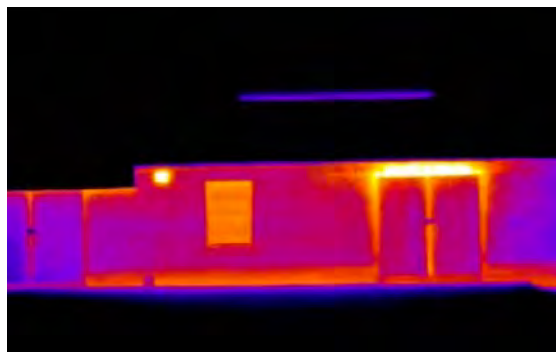
**Electricity Score:** N/A

Figures D-48 and D-49, respectively, show the aerial view and thermal image of Bldg 116, Camp Lejeune.

Figure D-48. Aerial view of Bldg 116, Camp Lejeune.



Figure D-49. Thermal image of Bldg 116, Camp Lejeune.



### D.11.2 Notable leaks at Bldg 116, Marine Corps Base Camp Lejeune, NC

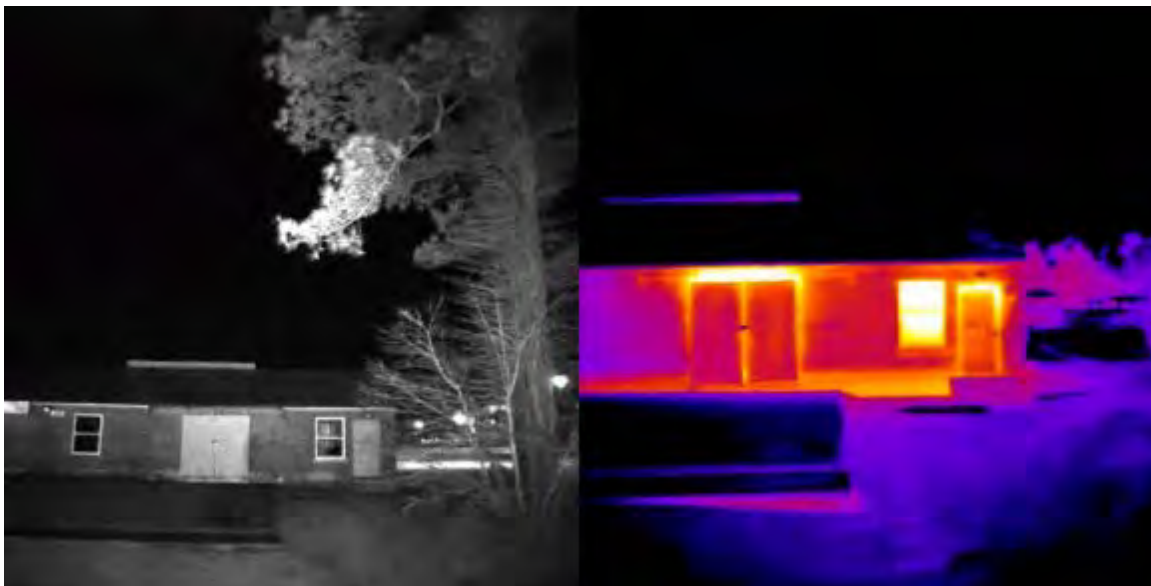
The wall of Bldg 116 is fairly emissive compared to most buildings on the base (Figure D-50). The door frame at timestamp 87:26 is also noticeably leaky.

Figure D-50. NIR image (left) and thermal image (right) of Bldg 116, Camp Lejeune.



The door frames and window frame visible at timestamp 87:43 are unusually leaky (Figure D-50).

Figure D-51. NIR image (left) and thermal image (right) of Bldg 116, Camp Lejeune. The door frames and window frame visible are unusually leaky.



### D.11.3 Envelope ECMs for Bldg 116, Marine Corps Base Camp Lejeune, NC

Figure D-52 shows the relative ROI for envelope ECMs for Bldg 116, Camp Lejeune.

Figure D-52. ECM profile for Bldg 116, Camp Lejeune.

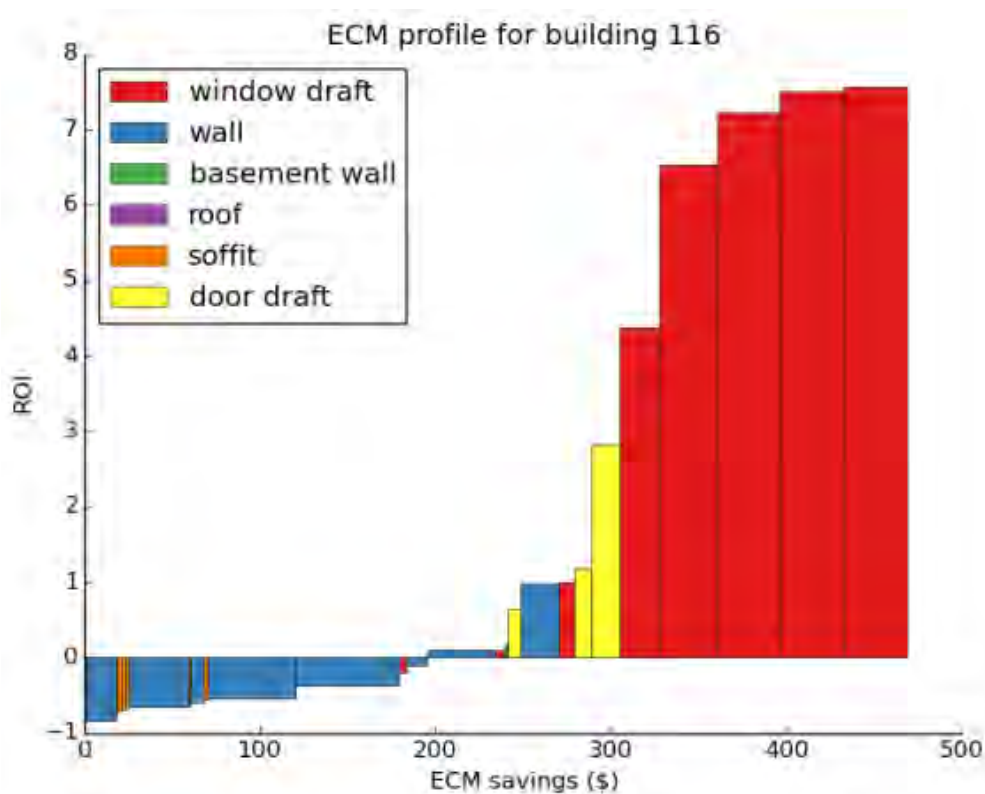


Table D-11 lists the recommended envelope ECMs for Bldg 116, Camp Lejeune.

Table D-11. Envelope ECMs for Bldg 116, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Window Frame Leaks	285	279	181	516	2.9
Improve Wall Insulation	209	205	133	2345	17.7
Seal Door Frame Leaks	52	51	33	193	5.9

Annual potential remediation savings for this building are \$346 and total payback is 8.8 years for envelope-related ECMs.



## D.12 Bldg 117

### D.12.1 Description of Bldg 116, Marine Corps Base Camp Lejeune, NC

**Name:** Maintenance Shop

**Use Type:** Office

**Square Footage:** 3,407

**Avg. Daily Electric Use:** Not Provided

**Electricity Score:** N/A

Figures D-53 and D-54, respectively, show the aerial view and thermal image of Bldg 117, Camp Lejeune.

Figure D-53. Aerial view of Bldg 117, Camp Lejeune.



Figure D-54. Thermal image of Bldg 117, Camp Lejeune.



### D.12.2 Notable leaks at Bldg 116, Marine Corps Base Camp Lejeune, NC

The wall of Bldg 117 at timestamp 290:20 (Figure D-55) is more emissive than the walls of most other buildings on the base. The soffits and window frames are also fairly emissive.



Figure D-55. NIR image (left) and thermal image (right) of Bldg 117, Camp Lejeune.



### D.12.3 Envelope ECMs for Bldg 116, Marine Corps Base Camp Lejeune, NC

Figure D-56 shows the relative ROI for envelope ECMs for Bldg 117, Camp Lejeune.

Figure D-56. ECM profile for Bldg 117, Camp Lejeune.

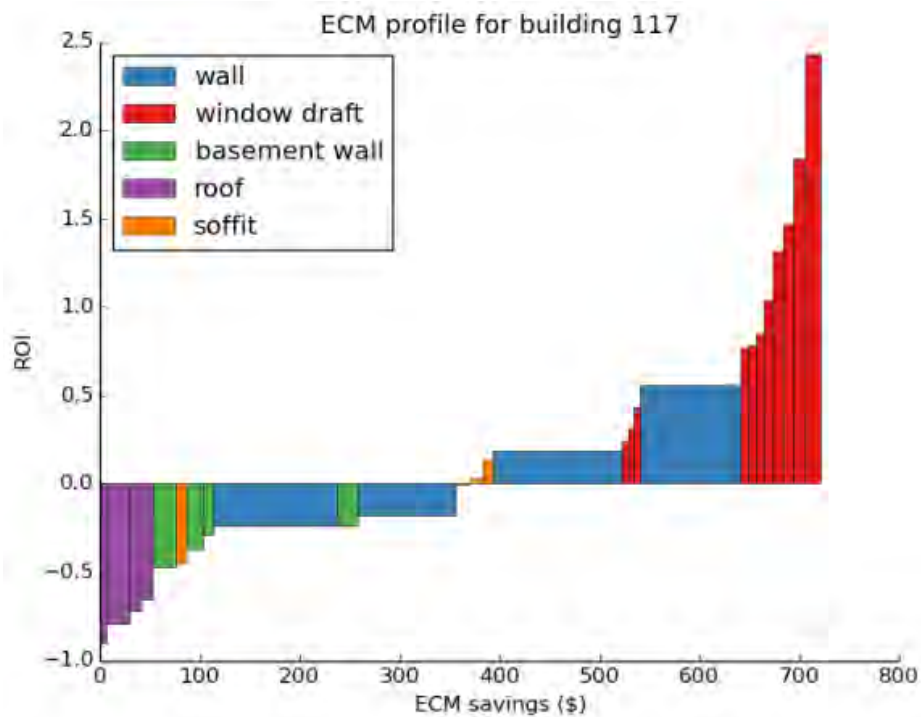


Table D-12 lists the recommended envelope ECMs for Bldg 117, Camp Lejeune.

Table D-12. Envelope ECMs for Bldg 117, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	717	702	454	6878	15.1
Seal Window Frame Leaks	153	150	97	712	7.3
Basement Wall Insulation	111	109	70	1666	23.7
Improve Soffit Insulation	75	73	48	823	17.3

Annual potential remediation savings for this building are \$669 and total payback is 15.1 years for envelope-related ECMs.

## D.13 Bldg 201

### D.13.1 Description of Bldg 201, Marine Corps Base Camp Lejeune, NC

**Name:** Indoor Physical Fitness Center

**Use Type:** Recreation

**Square Footage:** 16,922

**Avg. Daily Electric Use:** 1,010 kWh

**Electricity Score:** 70<sup>th</sup> Percentile

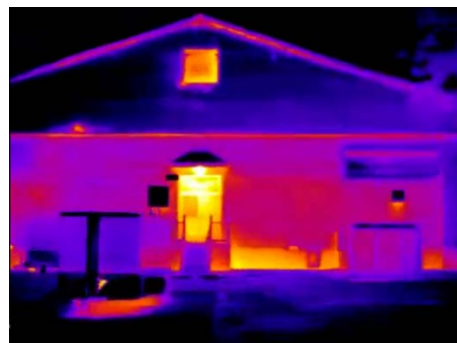
**Electricity Usage:** 21.7 kWh/sq ft/yr

Figures D-57 and D-58, respectively, show the aerial view and thermal image of Bldg 201, Camp Lejeune.

Figure D-57. Aerial view of Bldg 201, Camp Lejeune.



Figure D-58. Thermal image of Bldg 201, Camp Lejeune.



### D.13.2 Notable leaks at Bldg 201, Marine Corps Base Camp Lejeune, NC

The wall and roof of Bldg 201 are notable emissive, as shown at timestamp 111:58 (Figure D-59). There is a hot spot on the left side of the wall, as well as an apparent insulation hole near the top-left of the building.

Figure D-59. NIR image (left) and thermal image (right) of Bldg 201, Camp Lejeune.



### D.13.3 Envelope ECMs for Bldg 201, Marine Corps Base Camp Lejeune, NC

Figure D-60 shows the relative ROI for envelope ECMs for Bldg 201, Camp Lejeune.

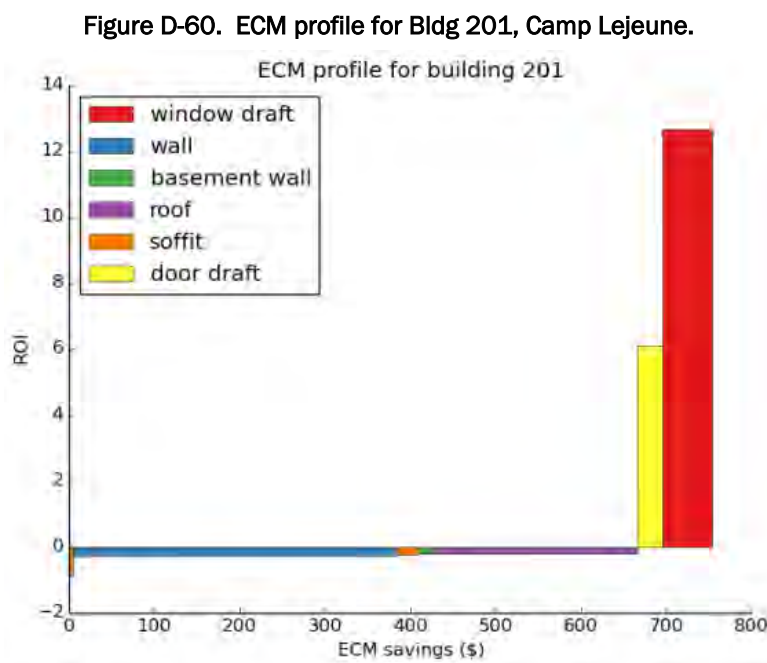


Table D-13 lists the recommended envelope ECMs for Bldg 201, Camp Lejeune.

Table D-13. Envelope ECMs for Bldg 201, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	598	586	379	8099	21.4
Improve Roof Insulation	376	368	238	4468	18.8

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Window Frame Leaks	92	90	58	64	1.1
Seal Door Frame Leaks	48	47	30	64	2.1
Improve Soffit Insulation	39	38	24	483	19.8
Basement Wall Insulation	30	29	19	362	19.0

Annual potential remediation savings for this building are \$749 and total payback is 18.1 years for envelope-related ECMs.

## D.14 Bldg 203

### D.14.1 Description of Bldg 203, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 3,431

**Avg. Daily Electric Use:** Not Provided

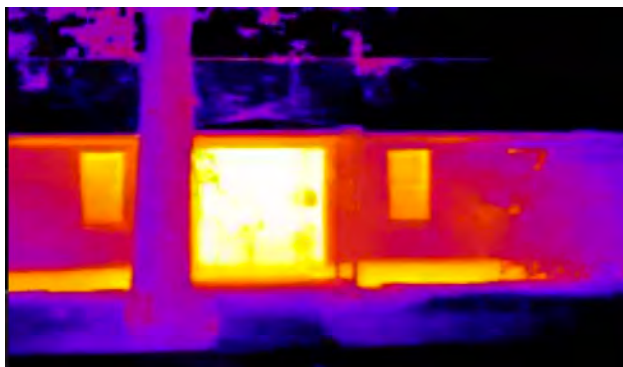
**Electricity Score:** N/A

Figures D-61 and D-62, respectively, show the aerial view and thermal image of Bldg 203, Camp Lejeune.

Figure D-61. Aerial view of Bldg 203, Camp Lejeune.



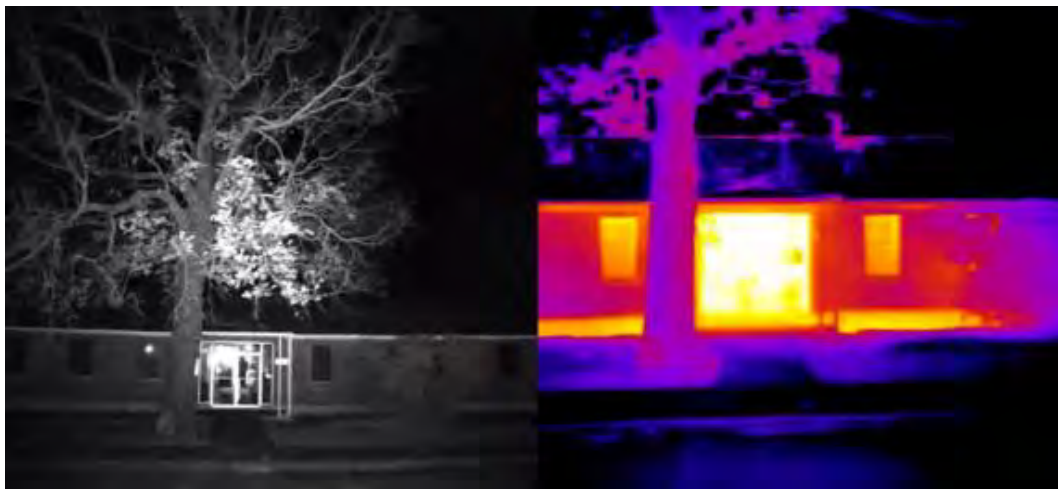
Figure D-62. Thermal image of Bldg 203, Camp Lejeune.



### D.14.2 Notable leaks at Bldg 203, Marine Corps Base Camp Lejeune, NC

The wall and exposed foundation of Bldg 203 as shown at timestamp 108:33 are both quite emissive and poorly insulated (Figure D-63). The windows and door frame are also more emissive than most.

Figure D-63. NIR image (left) and thermal image (right) of Bldg 203, Camp Lejeune.



#### D.14.3 Envelope ECMs for Bldg 203, Marine Corps Base Camp Lejeune, NC

Figure D-56 shows the relative ROI for envelope ECMs for Bldg 203, Camp Lejeune.

Figure D-64. ECM profile for Bldg 203, Camp Lejeune.

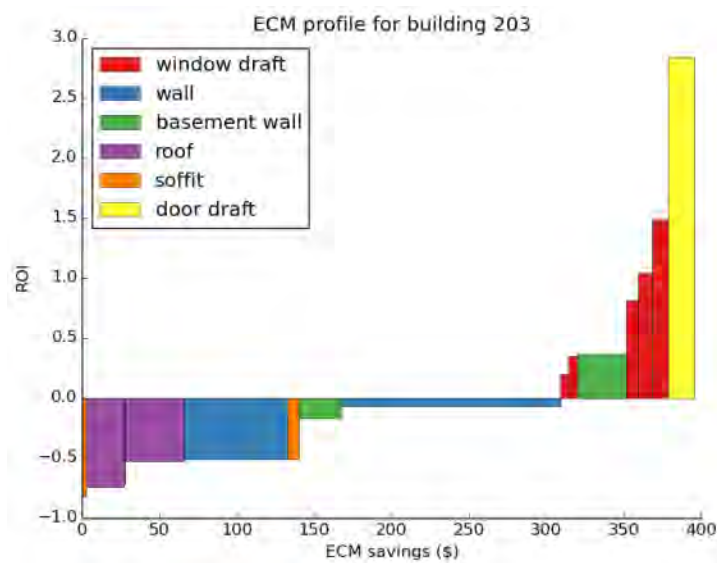


Table D-14 lists the recommended envelope ECMs for Bldg 203, Camp Lejeune.



Table D-14. Envelope ECMs for Bldg 203, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	223	219	142	2283	16.1
Basement Wall Insulation	93	91	59	847	14.3
Seal Window Frame Leaks	61	59	38	324	8.4
Seal Door Frame Leaks	26	26	17	65	3.9

Annual potential remediation savings for this building are \$256 and total payback is 13.8 years for envelope-related ECMs.

## D.15 Bldg 207

### D.15.1 Description of Bldg 207, Marine Corps Base Camp Lejeune, NC

**Name:** General Storage Shed

**Use Type:** Office

**Square Footage:** 3,691

**Avg. Daily Electric Use:** Not Provided

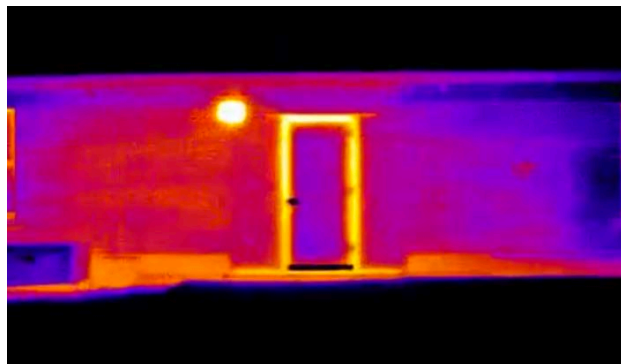
**Electricity Score:** N/A

Figures D-65 and D-66, respectively, show the aerial view and thermal image of Bldg 207, Camp Lejeune.

Figure D-65. Aerial view of Bldg 207, Camp Lejeune.



Figure D-66. Thermal image of Bldg 207, Camp Lejeune.



### D.15.2 Notable leaks at Bldg 207, Marine Corps Base Camp Lejeune, NC

The wall of Bldg 207 at timestamp 302:44 is notable hot, with some discrete hot spots near the center of the image (Figure D-67).

Figure D-67. NIR image (left) and thermal image (right) of Bldg 207, Camp Lejeune.



The window frame and the wall to the right of it at timestamp 302:46 are quite hot and may be effectively remediated with improved insulation and air sealing (Figure D-68).

Figure D-68. NIR image (left) and thermal image (right) of Bldg 207, Camp Lejeune. The window frame and the wall to the right of it are quite hot.



#### **D.15.3 Envelope ECMs for Bldg 207, Marine Corps Base Camp Lejeune, NC**

Figure D-69 shows the relative ROI for envelope ECMs for Bldg 207, Camp Lejeune.

Figure D-69. ECM profile for Bldg 207, Camp Lejeune.

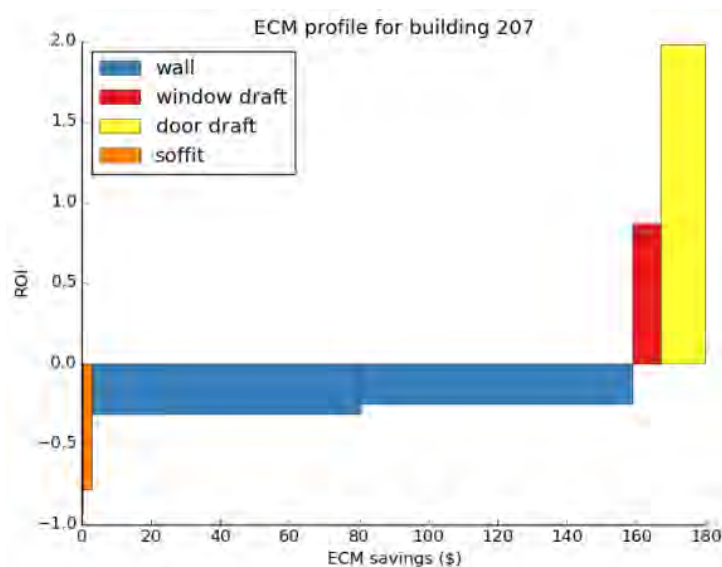


Table D-15 lists the recommended envelope ECMs for Bldg 207, Camp Lejeune.

Table D-15. Envelope ECMs for Bldg 207, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	246	241	156	3269	21.0
Seal Door Frame Leaks	20	20	13	64	5.0

Annual potential remediation savings for this building are \$169 and total payback is 19.8 years for envelope-related ECMs.

## D.16 Bldg 217

### D.16.1 Description of Bldg 217, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 26,602

**Avg. Daily Electric Use:** 427 kWh

**Electricity Score:** 5th Percentile

Bldg 217 (Figures D-70 and D-71) has an electricity usage of 5.9 kWh/sq ft/yr.



Figure D-70. Aerial view of Bldg 217, Camp Lejeune.



Figure D-71. Thermal image of Bldg 217, Camp Lejeune.



#### **D.16.2 Notable leaks at Bldg 217, Marine Corps Base Camp Lejeune, NC**

The wall of Bldg 217 at timestamp 308:58 is highly emissive, particularly in the right side of the image and in the back-right corner (Figure D-72).

Figure D-72. NIR image (left) and thermal image (right) of Bldg 217, Camp Lejeune.



The wall in the back left and right of the image at timestamp 309:01 is very highly emissive, which likely indicates poor insulation (Figure D-73).

Figure D-73. NIR image (left) and thermal image (right) of Bldg 217, Camp Lejeune. The wall in the rear left and rear right of the image is very highly emissive.



### D.16.3 Envelope ECMs for Bldg 217, Marine Corps Base Camp Lejeune, NC

Figure D-74 shows the relative ROI for envelope ECMs for Bldg 217, Camp Lejeune.

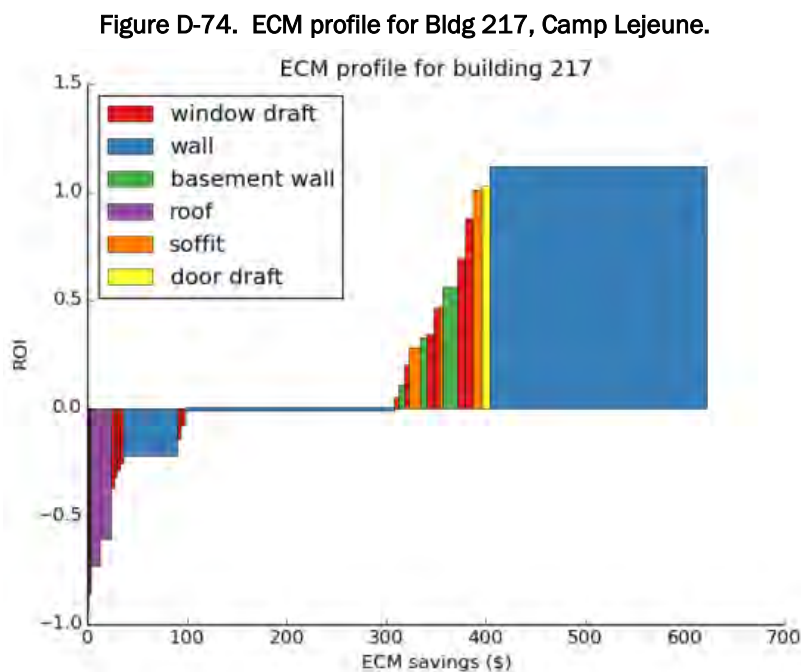


Table D-16 lists the recommended envelope ECMs for Bldg 217, Camp Lejeune

Table D-16. Envelope ECMs for Bldg 217, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	760	744	482	5783	12.0
Seal Window Frame Leaks	90	88	57	776	13.7
Basement Wall Insulation	43	42	27	293	10.8
Improve Soffit Insulation	37	36	23	230	9.9

Annual potential remediation savings for this building are \$589 and total payback is 12.0 years for envelope-related ECMs.

## D.17 Bldg 233

### D.17.1 Description of Bldg 233, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Building

**Use Type:** Office

**Square Footage:** 4,068

**Avg. Daily Electric Use:** Not Provided

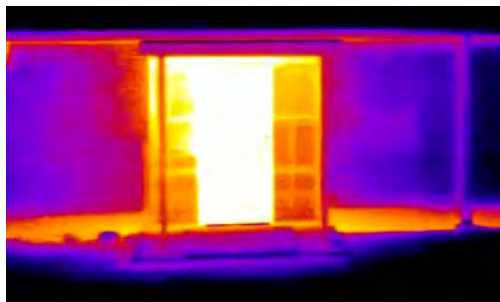
**Electricity Score:** N/A

Figures D-75 and D-76, respectively, show the aerial view and thermal image of Bldg 233, Camp Lejeune.

Figure D-75. Aerial view of Bldg 233, Camp Lejeune.



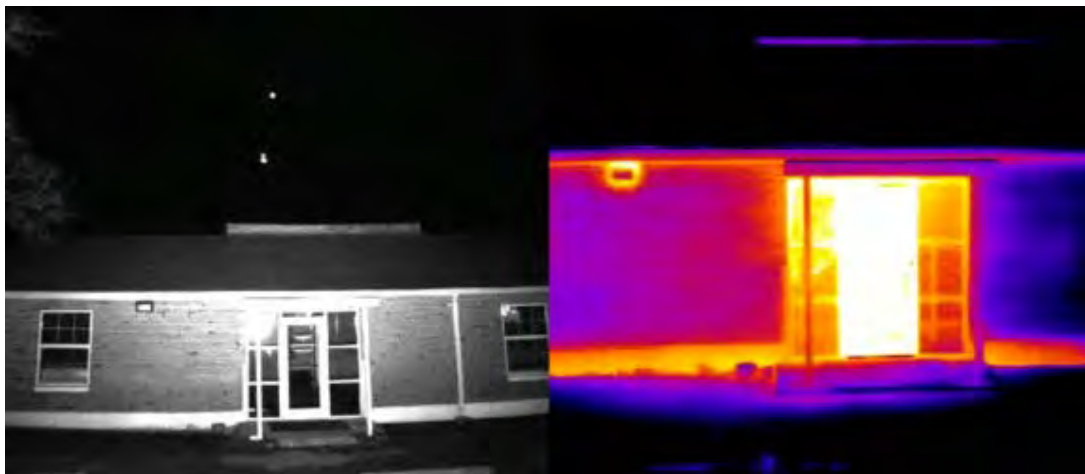
Figure D-76. Thermal image of Bldg 233, Camp Lejeune.



### D.17.2 Notable leaks at Bldg 233, Marine Corps Base Camp Lejeune, NC

The foundation wall, door frame, and soffit at timestamp 304:06 are all highly emissive (Figure D-77).

Figure D-77. NIR image (left) and thermal image (right) of Bldg 233, Camp Lejeune.



#### D.17.3 Envelope ECMs for Bldg 233, Marine Corps Base Camp Lejeune, NC

Figure D-78 shows the relative ROI for envelope ECMs for Bldg 233, Camp Lejeune.

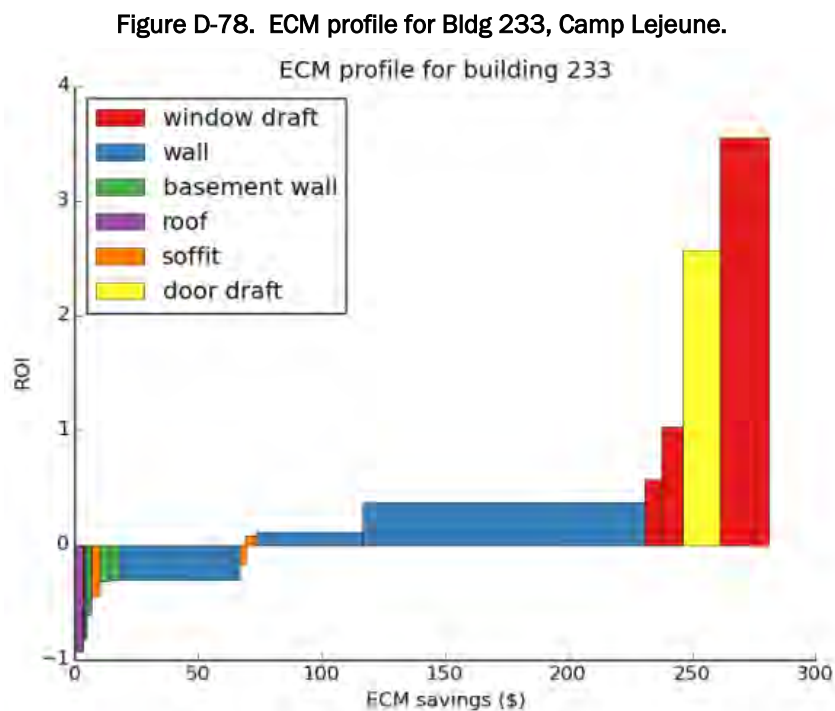


Table D-17 lists the recommended envelope ECMs for Bldg 233, Camp Lejeune.

Table D-17. Envelope ECMs for Bldg 233, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	325	318	206	2879	14.0
Seal Window Frame Leaks	55	54	35	195	5.5
Seal Door Frame Leaks	24	24	15	64	4.2
Improve Soffit Insulation	16	16	10	201	19.3

Annual potential remediation savings for this building are \$267 and total payback is 12.5 years for envelope-related ECMs.

## D.18 Bldg 235

### D.18.1 Description of Bldg 235, Marine Corps Base Camp Lejeune, NC

**Name:** Bus Station

**Use Type:** Misc.

**Square Footage:** 8,592

**Avg. Daily Electric Use:** Not Provided

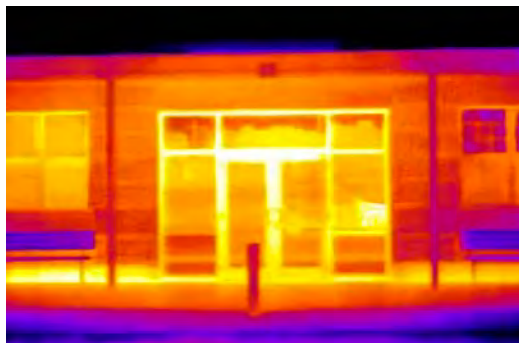
**Electricity Score:** N/A

Figures D-79 and D-80, respectively, show the aerial view and thermal image of Bldg 235, Camp Lejeune.

Figure D-79. Aerial view of Bldg 235, Camp Lejeune.



Figure D-80. Thermal image of Bldg 235, Camp Lejeune.

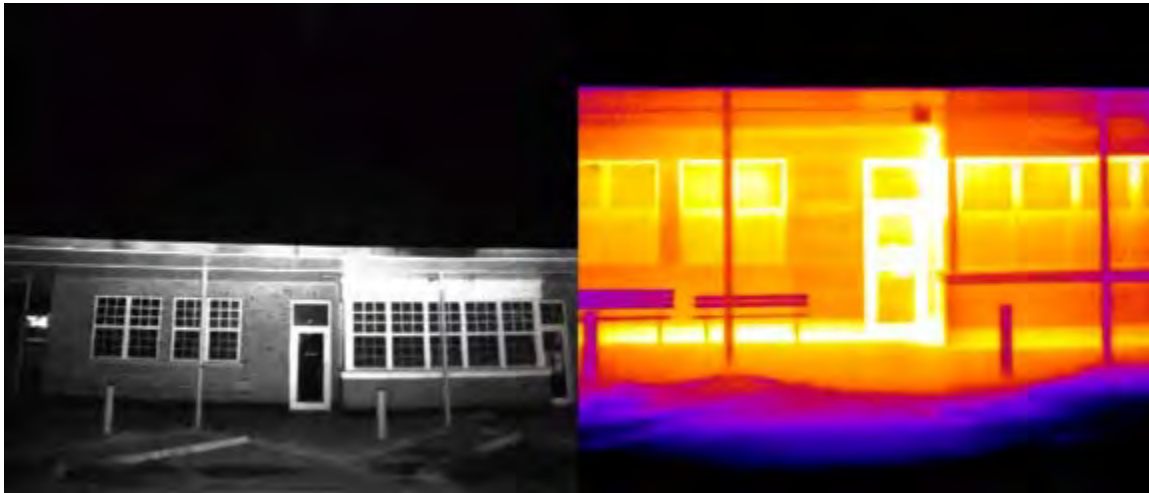


### D.18.2 Notable leaks at Bldg 235, Marine Corps Base Camp Lejeune, NC

Bldg 235 has generally poor insulation in all of its walls (Figure D-81). This can be seen at timestamp 110:43, in addition to a highly emissive door frame indicating air leakage.

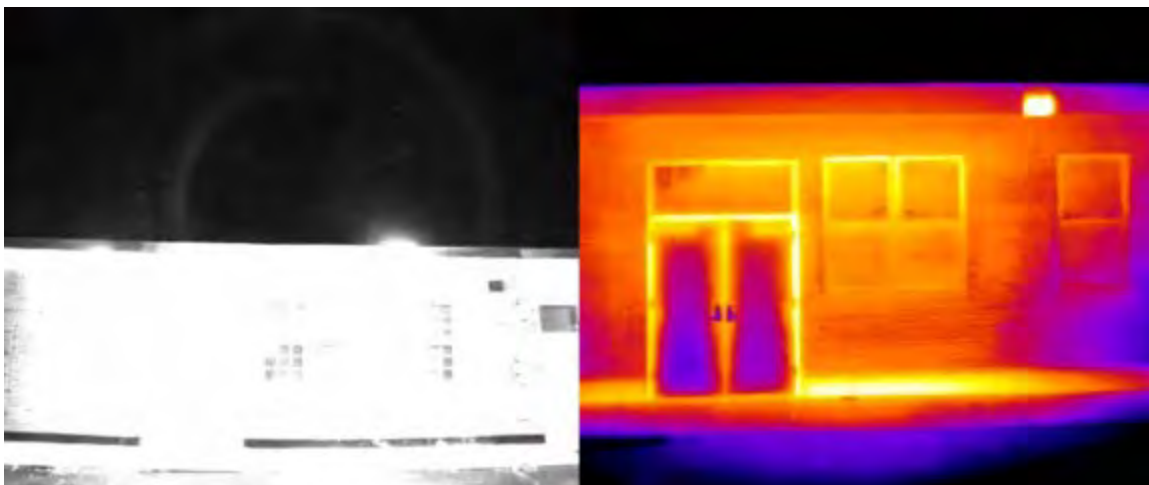


Figure D-81. NIR image (left) and thermal image (right) of Bldg 235, Camp Lejeune.



The wall at timestamp 110:48 is also quite emissive, as is the door frame near the left side of the image (Figure D-82).

Figure D-82. NIR image (left) and thermal image (right) of Bldg 235, Camp Lejeune. The wall and door frame are also quite emissive.



### D.18.3 Envelope ECMs for Bldg 235, Marine Corps Base Camp Lejeune, NC

Figure D-83 shows the relative ROI for envelope ECMs for Bldg 235, Camp Lejeune.

Figure D-83. ECM profile for Bldg 235, Camp Lejeune.

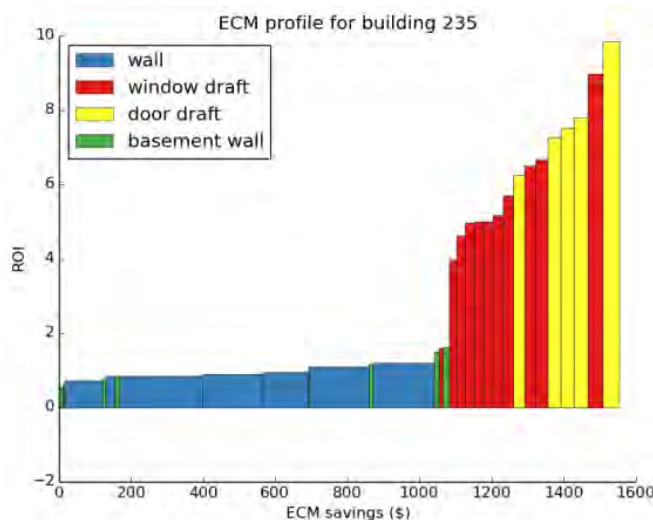


Table D-18 lists the recommended envelope ECMs for Bldg 235, Camp Lejeune.

Table D-18. Envelope ECMs for Bldg 235, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1557	1525	987	7643	7.7
Seal Window Frame Leaks	470	460	298	711	2.4
Seal Door Frame Leaks	295	289	187	322	1.7
Basement Wall Insulation	131	128	83	619	7.5

Annual potential remediation savings for this building are \$1,555 and total payback is 6 years for envelope-related ECMs.

## D.19 Bldg 322

### D.19.1 Description of Bldg 322, Marine Corps Base Camp Lejeune, NC

**Name:** North Section Building

**Use Type:** Office

**Square Footage:** 62,793

**Avg. Daily Electric Use:** 1,329 kWh

**Electricity Score:** 10th Percentile

**Electricity Usage:** 7.7 kWh/sq ft/yr

Figures D-84 and D-85, respectively, show the aerial view and thermal image of Bldg 322, Camp Lejeune.

Figure D-84. Aerial view of Bldg 322, Camp Lejeune.



Figure D-85. Thermal image of Bldg 322, Camp Lejeune.



### D.19.2 Notable leaks at Bldg 322, Marine Corps Base Camp Lejeune, NC

The exposed foundation visible at timestamp 312:50 is notably emissive, as is the window frame near the center of the image (Figure D-86).

Figure D-86. NIR image (left) and thermal image (right) of Bldg 322, Camp Lejeune.



The window frame near the center of the image at timestamp 312:57 is quite emissive, as is the foundation and soffit (Figure D-87).



Figure D-87. NIR image (left) and thermal image (right) of Bldg 322, Camp Lejeune. The window frame, foundation and soffit are also quite emissive.



### D.19.3 Envelope ECMs for Bldg 322, Marine Corps Base Camp Lejeune, NC

Figure D-88 shows the relative ROI for envelope ECMs for Bldg 322, Camp Lejeune.

Figure D-88. ECM profile for Bldg 322, Camp Lejeune.

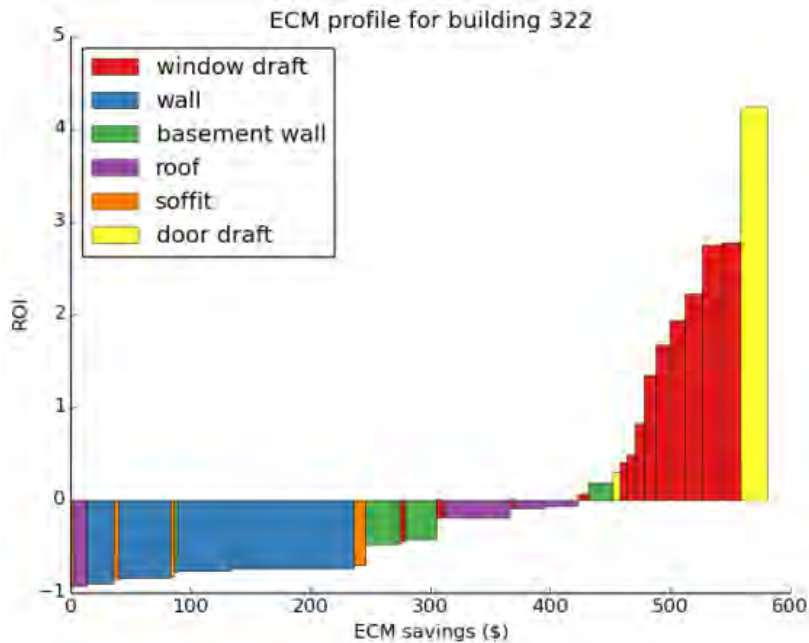


Table D-19 lists the recommended envelope ECMs for Bldg 322, Camp Lejeune.

Table D-19. Envelope ECMs for Bldg 322, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Window Frame Leaks	198	194	126	1036	8.2
Improve Roof Insulation	168	165	107	1860	17.4
Basement Wall Insulation	118	115	75	1762	23.6
Seal Door Frame Leaks	44	43	28	129	4.6

Annual potential remediation savings for this building are \$335 and total payback is 14.3 years for envelope-related ECMs.

## D.20 Bldg 401

### D.20.1 Description of Bldg 401, Marine Corps Base Camp Lejeune, NC

**Name:** Gymnasium

**Use Type:** Recreation

**Square Footage:** 12,402

**Avg. Daily Electric Use:** 204.7 kWh

**Electricity Score:** 20th Percentile

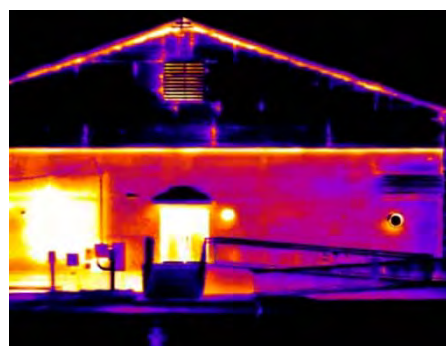
**Electricity Usage:** 6.0 kWh/sq ft/yr

Figures D-89 and D-90, respectively, show the aerial view and thermal image of Bldg 401, Camp Lejeune.

Figure D-89. Aerial view of Bldg 401, Camp Lejeune.



Figure D-90. Thermal image of Bldg 401, Camp Lejeune.



### D.20.2 Notable leaks at Bldg 401, Marine Corps Base Camp Lejeune, NC

There is a large poorly insulated hot spot on the left side of the image at timestamp 354:09. The soffits at the top of the brick wall and at the roof-line are both quite poorly insulated (Figure D-91).

Figure D-91. NIR image (left) and thermal image (right) of Bldg 401, Camp Lejeune.



### D.20.3 Envelope ECMs for Bldg 401, Marine Corps Base Camp Lejeune, NC

Figure D-92 shows the relative ROI for envelope ECMs for Bldg 401, Camp Lejeune.

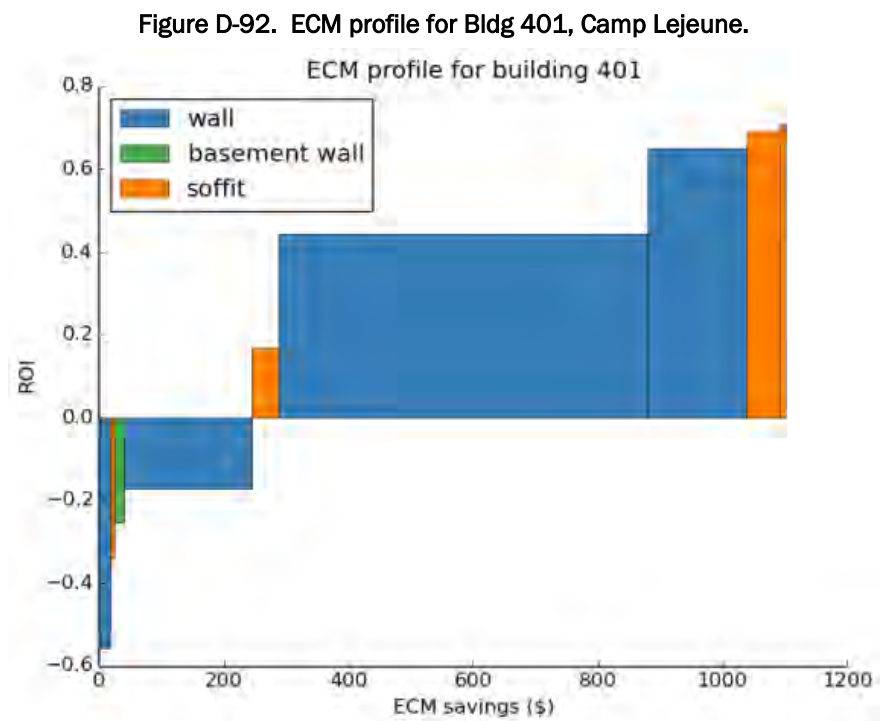


Table D-20 lists the recommended envelope ECMs for Bldg 401, Camp Lejeune.

Table D-20. Envelope ECMs for Bldg 401, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1508	1477	956	11325	11.8
Improve Soffit Insulation	177	174	112	1260	11.2
Basement Wall Insulation	23	23	15	297	20.1

Annual potential remediation savings for this building are \$1,083 and total payback is 11.9 years for envelope-related ECMs.

## D.21 Bldg 407

### D.21.1 Description of Bldg 407, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 26,602

**Avg. Daily Electric Use:** 1,265 kWh

**Electricity Score:** 70th Percentile

Bldg 407 (Figures D-93 and D-94) has an electricity usage of 17.3 kWh/sq ft/yr

Figure D-93. Aerial view of Bldg 407, Camp Lejeune.



Figure D-94. Thermal image of Bldg 407, Camp Lejeune.



### D.21.2 Notable leaks at Bldg 407, Marine Corps Base Camp Lejeune, NC

The walls of Bldg 407 at timestamp 354:25 are highly emissive, with hot spots on the right side of the image and in the back center (Figure D-95).

Figure D-95. NIR image (left) and thermal image (right) of Bldg 407, Camp Lejeune.



The wall in the left corner of the back of the image at timestamp 354:28 is notably hot, which indicates poor insulation (Figure D-96).

Figure D-96. NIR image (left) and thermal image (right) of Bldg 407, Camp Lejeune. The wall in the left and right rear corners is notably hot, which indicates poor insulation.



### D.21.3 Envelope ECMs for Bldg 407, Marine Corps Base Camp Lejeune, NC

Figure D-97 shows the relative ROI for envelope ECMs for Bldg 407, Camp Lejeune.

Figure D-97. ECM profile for Bldg 407, Camp Lejeune.

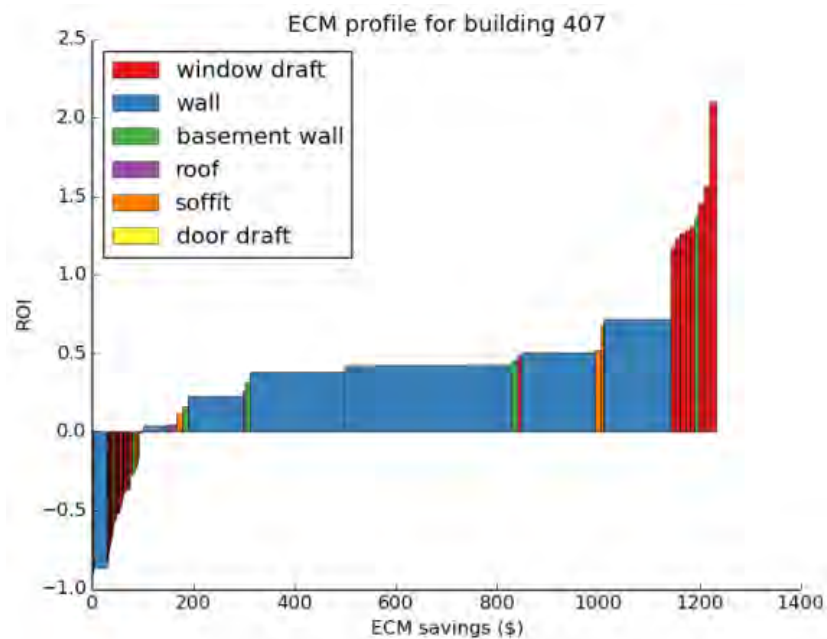


Table D-21 lists the recommended envelope ECMs for Bldg 407, Camp Lejeune.

Table D-21. Envelope ECMs for Bldg 407, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1503	1472	953	10144	10.6
Seal Window Frame Leaks	182	179	116	1163	10.1
Basement Wall Insulation	79	77	50	623	12.5
Improve Soffit Insulation	60	58	38	497	13.1
Improve Roof Insulation	32	32	21	286	13.9

Annual potential remediation savings for this building are \$1,177 and total payback is 10.8 years for envelope-related ECMs.



## D.22 Bldg 408

### D.22.1 Description of Bldg 408, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 21,759

**Avg. Daily Electric Use:** 358.4

**Electricity Score:** 25th Percentile

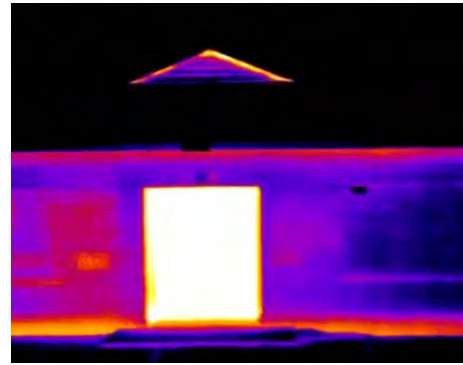
**Electricity Usage:** 6.0 kWh/sq ft/yr

Figures D-98 and D-99, respectively, show the aerial view and thermal image of Bldg 408, Camp Lejeune.

Figure D-98. Aerial view of Bldg 408, Camp Lejeune.



Figure D-99. Thermal image of Bldg 408, Camp Lejeune.



### D.22.2 Notable leaks at Bldg 408, Marine Corps Base Camp Lejeune, NC

There is a large poorly insulated hot spot at timestamp 356:55 on the left side of the image. The door frame in the center of the image is also fairly leaky and would benefit from air sealing (Figure D-100).

Figure D-100. NIR image (left) and thermal image (right) of Bldg 408, Camp Lejeune.



The wall at timestamp 356:57 has a hot spot around the center of the image, and the exposed foundation/basement wall is also quite emissive (Figure D-101).

Figure D-101. NIR image (left) and thermal image (right) of Bldg 408, Camp Lejeune. The wall has a hot spot around the center of the image, and the exposed foundation/basement wall is also quite emissive.



### D.22.3 Envelope ECMs for Bldg 408, Marine Corps Base Camp Lejeune, NC

Figure D-102 shows the relative ROI for envelope ECMs for Bldg 408, Camp Lejeune.



Figure D-102. ECM profile for Bldg 408, Camp Lejeune.

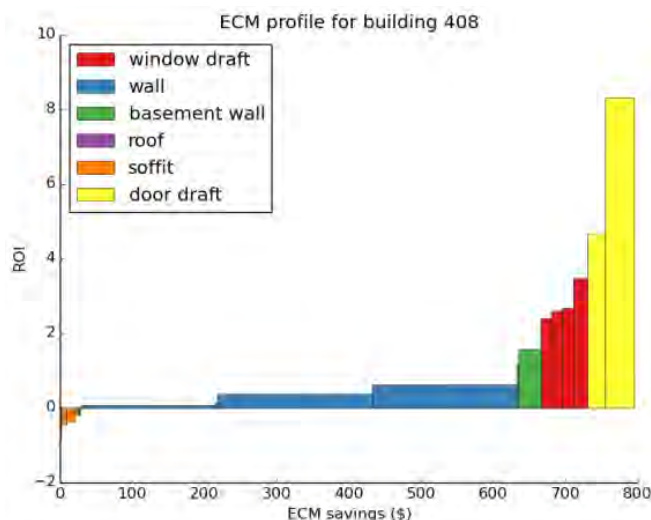


Table D-22 lists the recommended envelope ECMs for Bldg 408, Camp Lejeune.

Table D-22. Envelope ECMs for Bldg 408, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	944	925	599	6834	11.4
Seal Window Frame Leaks	103	101	65	258	4.0
Seal Door Frame Leaks	100	98	64	127	2.0
Basement Wall Insulation	61	60	39	308	7.9
Improve Soffit Insulation	35	34	22	527	23.9

Annual potential remediation savings for this building are \$789 and total payback is 10.2 years for envelope-related ECMs.

## D.23 Bldg 424

### D.23.1 Description of Bldg 424, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 22,867

**Avg. Daily Electric Use:** Not Provided

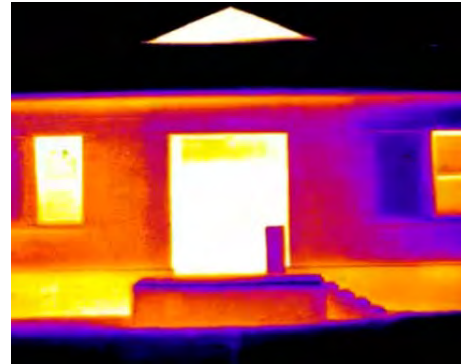
**Electricity Score:** N/A

Figures D-103 and D-104, respectively, show the aerial view and thermal image of Bldg 424, Camp Lejeune.

Figure D-103. Aerial view of Bldg 424, Camp Lejeune.



Figure D-104. Thermal image of Bldg 424, Camp Lejeune.



### D.23.2 Notable leaks at Bldg 424, Marine Corps Base Camp Lejeune, NC

The walls of Bldg 424 appear poorly insulated, particularly the portion on the left side of the image shown at timestamp 356:22 (Figure D-105).

Figure D-105. NIR image (left) and thermal image (right) of Bldg 424, Camp Lejeune.



### D.23.3 Envelope ECMs for Bldg 424, Marine Corps Base Camp Lejeune, NC

Figure D-106 shows the relative ROI for envelope ECMs for Bldg 424, Camp Lejeune.

Figure D-106. ECM profile for Bldg 424, Camp Lejeune.

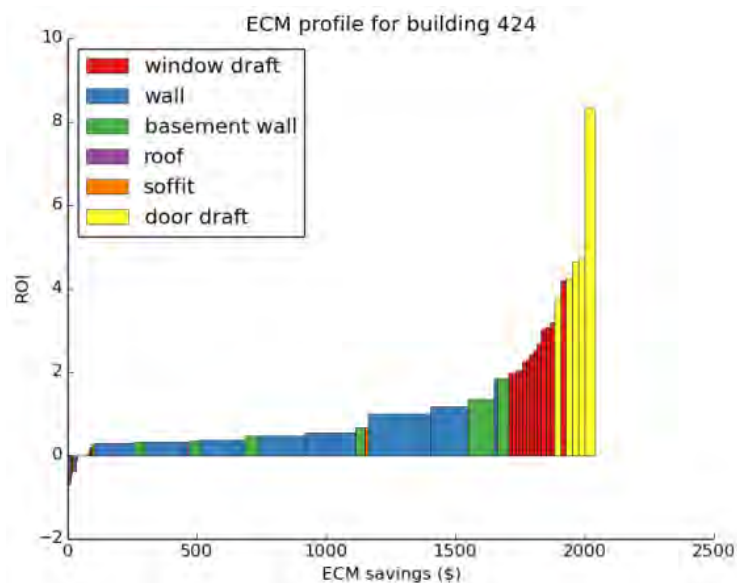


Table D-23 lists the recommended envelope ECMs for Bldg 424, Camp Lejeune.

Table D-23. Envelope ECMs for Bldg 424, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1994	1953	1264	12177	9.6
Basement Wall Insulation	560	548	355	3249	9.2
Seal Window Frame Leaks	332	325	211	970	4.6
Seal Door Frame Leaks	208	204	132	322	2.4
Improve Soffit Insulation	78	77	50	735	14.8
Improve Roof Insulation	25	24	16	294	18.6

Annual potential remediation savings for this building are \$2,026 and total payback is 8.8 years for envelope-related ECMs.

## D.24 Bldg 430

### D.24.1 Description of Bldg 430, Marine Corps Base Camp Lejeune, NC

**Name:** Small Arms Range

**Use Type:** Misc.

**Square Footage:** 7,536

**Avg. Daily Electric Use:** Not Provided

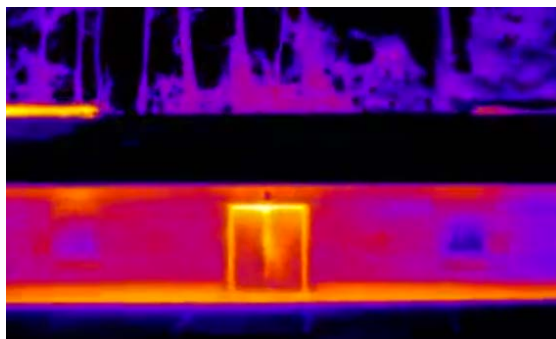
**Electricity Score:** N/A

Figures D-107 and D-108, respectively, show the aerial view and thermal image of Bldg 430, Camp Lejeune.

Figure D-107. Aerial view of Bldg 430, Camp Lejeune.



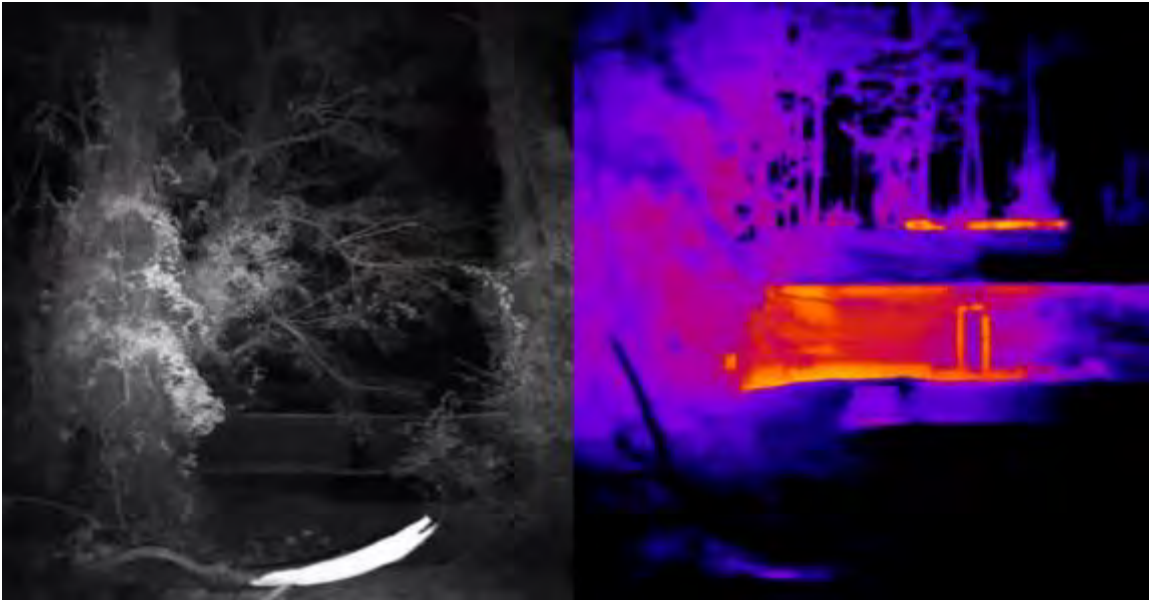
Figure D-108. Thermal image of Bldg 430, Camp Lejeune.



### D.24.2 Notable leaks at Bldg 430, Marine Corps Base Camp Lejeune, NC

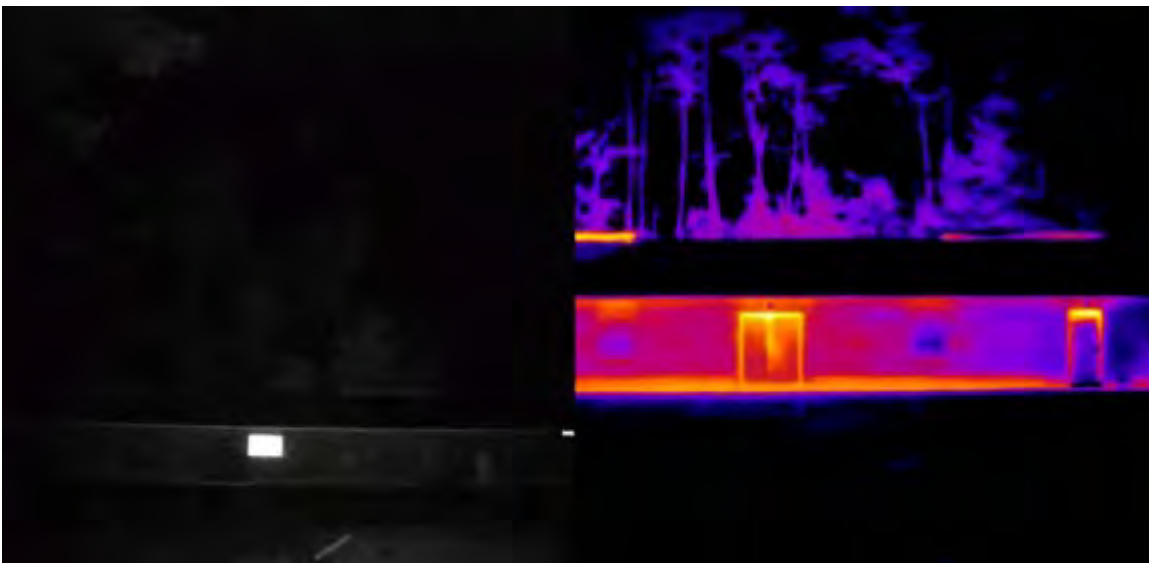
The walls of Bldg 430 are noticeably hot, as shown at timestamp 163:58 (Figure D-109). There is a hot spot in the wall on the left of the image, as well as around the door frame on the right side of the image.

Figure D-109. NIR image (left) and thermal image (right) of Bldg 430, Camp Lejeune.



The door frame at the center of the image at timestamp 164:00 is fairly emissive (Figure D-110).

Figure D-110. NIR image (left) and thermal image (right) of Bldg 430, Camp Lejeune. The door frame at the center of the image is fairly emissive.



#### **D.24.3 Envelope ECMs for Bldg 430, Marine Corps Base Camp Lejeune, NC**

Figure D-111 shows the relative ROI for envelope ECMs for Bldg 430, Camp Lejeune.

Figure D-111. ECM profile for Bldg 430, Camp Lejeune.

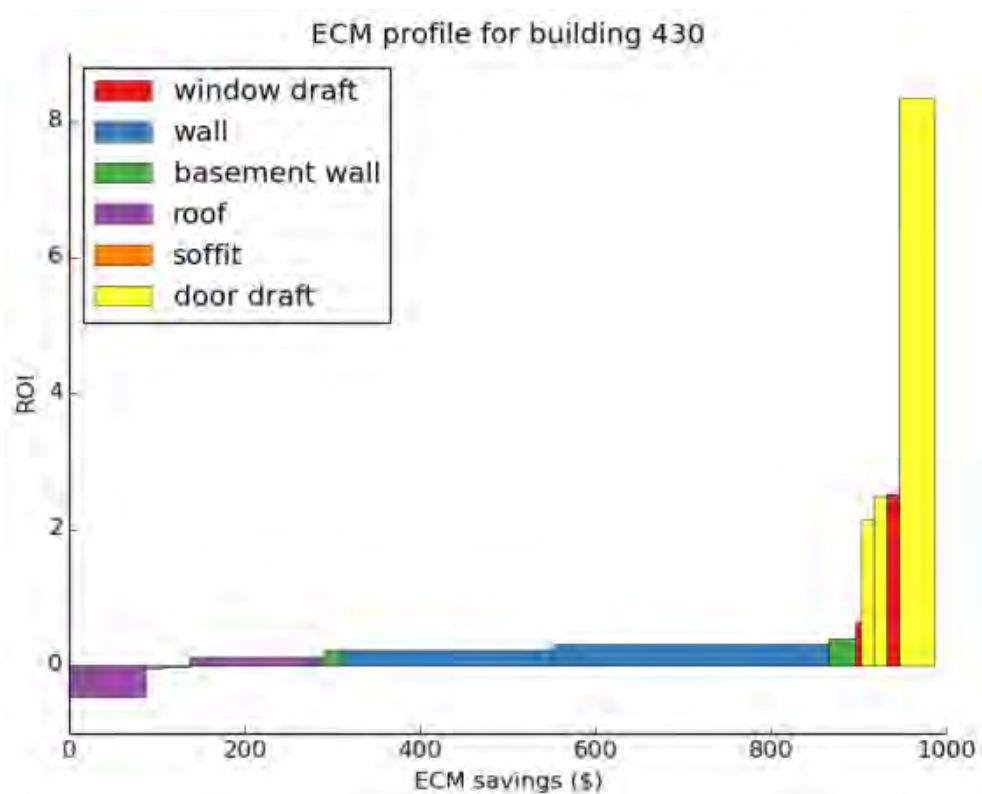


Table D-24 lists the recommended envelope ECMs for Bldg 430, Camp Lejeune.

Table D-24. Envelope ECMs for Bldg 430, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	874	857	554	6542	11.8
Improve Roof Insulation	378	370	240	4502	18.8
Basement Wall Insulation	112	110	71	892	12.6
Seal Door Frame Leaks	109	106	69	194	2.8
Improve Soffit Insulation	49	48	31	486	15.6
Seal Window Frame Leaks	35	35	22	130	5.8

Annual potential remediation savings for this building are \$987 and total payback is 12.9 years for envelope-related ECMs.



## D.25 Bldg 508

### D.25.1 Description of Bldg 508, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 23,073

**Avg. Daily Electric Use:** 202.6 kWh

**Electricity Score:** 5th Percentile

**Electricity Usage:** 3.2 kWh/sq ft/yr.

Figures D-112 and D-113, respectively, show the aerial view and thermal image of Bldg 508, Camp Lejeune.

Figure D-112. Aerial view of Bldg 508, Camp Lejeune.



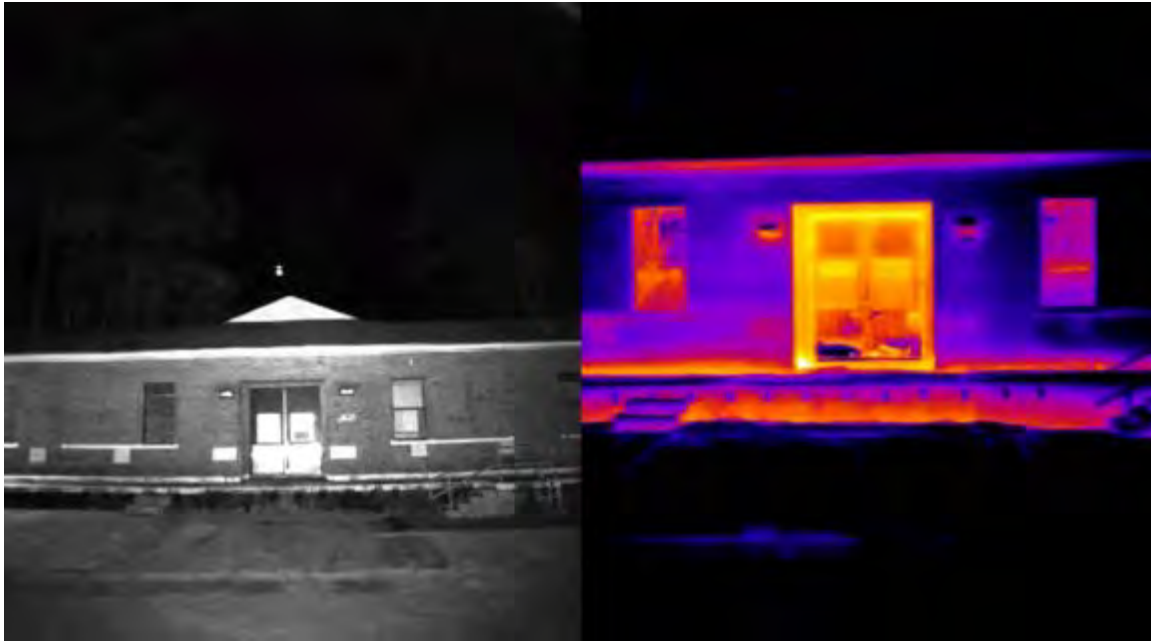
Figure D-113. Thermal image of Bldg 508, Camp Lejeune.



### D.25.2 Notable leaks at Bldg 508, Marine Corps Base Camp Lejeune, NC

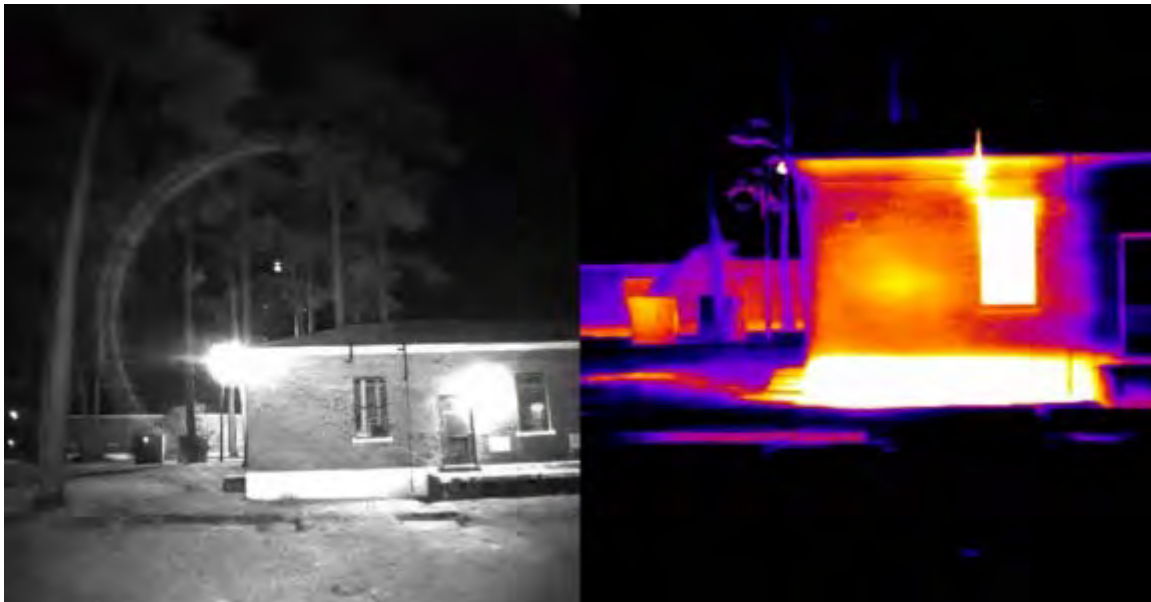
The door frame at timestamp 353:20 is quite emissive, which indicates potential air leaks (Figure D-114).

Figure D-114. NIR image (left) and thermal image (right) of Bldg 508, Camp Lejeune.



The wall in the center of the image at timestamp 353:22 is highly emissive, with a large warm hot spot in the center and an emissive foundation/basement wall (Figure D-115).

Figure D-115. NIR image (left) and thermal image (right) of Bldg 508, Camp Lejeune. The wall in the center of the image is highly emissive, with a large warm hot spot in the center and an emissive foundation/basement wall.





### D.25.3 Envelope ECMs for Bldg 508, Marine Corps Base Camp Lejeune, NC

Figure D-116 shows the relative ROI for envelope ECMs for Bldg 508, Camp Lejeune.

Figure D-116. ECM profile for Bldg 508, Camp Lejeune.

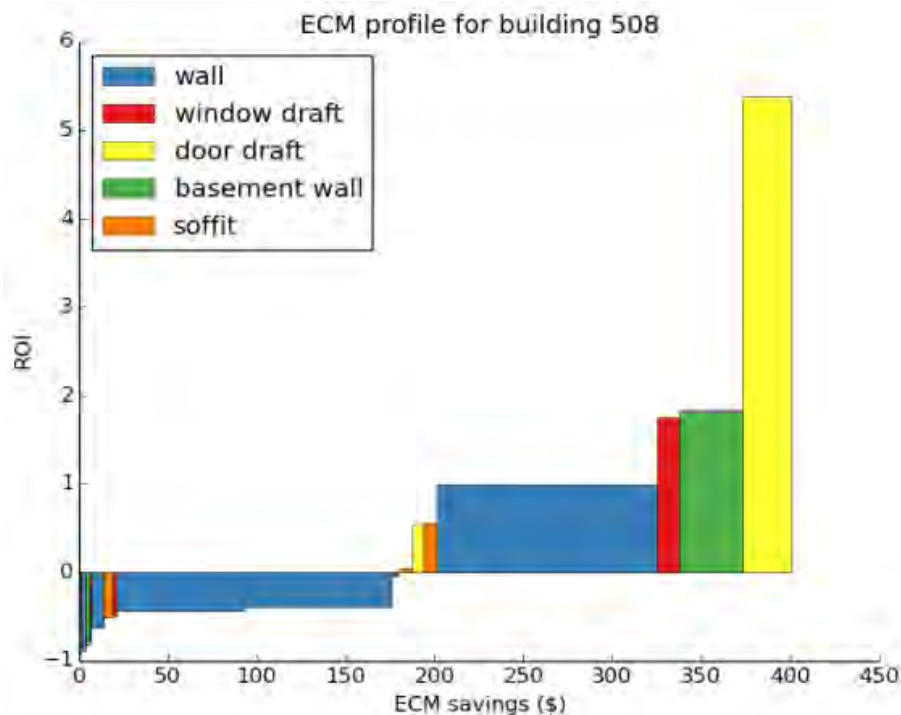


Table D-25 lists the recommended envelope ECMs for Bldg 508, Camp Lejeune.

Table D-25. Envelope ECMs for Bldg 508, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	439	430	278	4870	17.5
Basement Wall Insulation	57	56	36	190	5.3
Seal Door Frame Leaks	54	52	34	129	3.8
Seal Window Frame Leaks	25	25	16	130	8.1
Improve Soffit Insulation	24	24	15	183	12.0

Annual potential remediation savings for this building are \$379 and total payback is 14.5 years for envelope-related ECMs.

## D.26 Bldg 509

### D.26.1 Description of Bldg 509, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Office

**Square Footage:** 23,073

**Avg. Daily Electric Use:** 276 kWh

**Electricity Score:** 5th Percentile

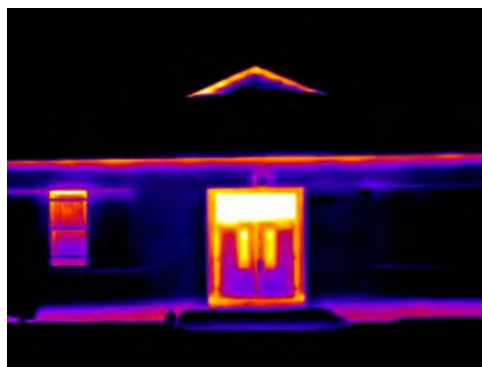
**Electricity Usage:** 4.4 kWh/sq ft/yr.

Figures D-117 and D-118, respectively, show the aerial view and thermal image of Bldg 509, Camp Lejeune.

Figure D-117. Aerial view of Bldg 509, Camp Lejeune.



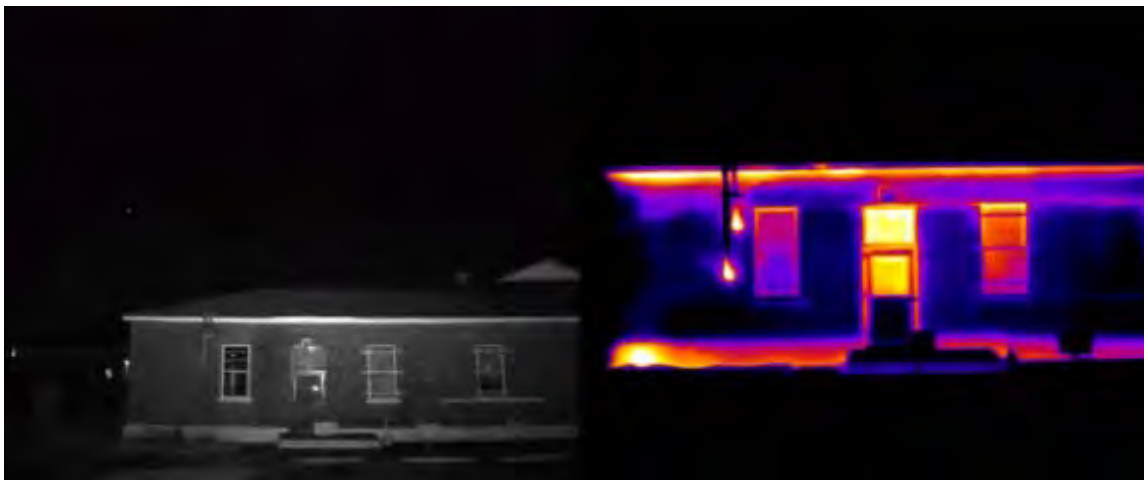
Figure D-118. Thermal image of Bldg 509, Camp Lejeune.



### D.26.2 Notable leaks at Bldg 509, Marine Corps Base Camp Lejeune, NC

The soffits at timestamp 169:06 are noticeably emissive, and there is a hot strip to the right of the image above the window (Figure D-119).

Figure D-119. NIR image (left) and thermal image (right) of Bldg 509, Camp Lejeune.



### D.26.3 Envelope ECMs for Bldg 509, Marine Corps Base Camp Lejeune, NC

Figure D-120 shows the relative ROI for envelope ECMs for Bldg 509, Camp Lejeune.

Figure D-120. ECM profile for Bldg 509, Camp Lejeune.

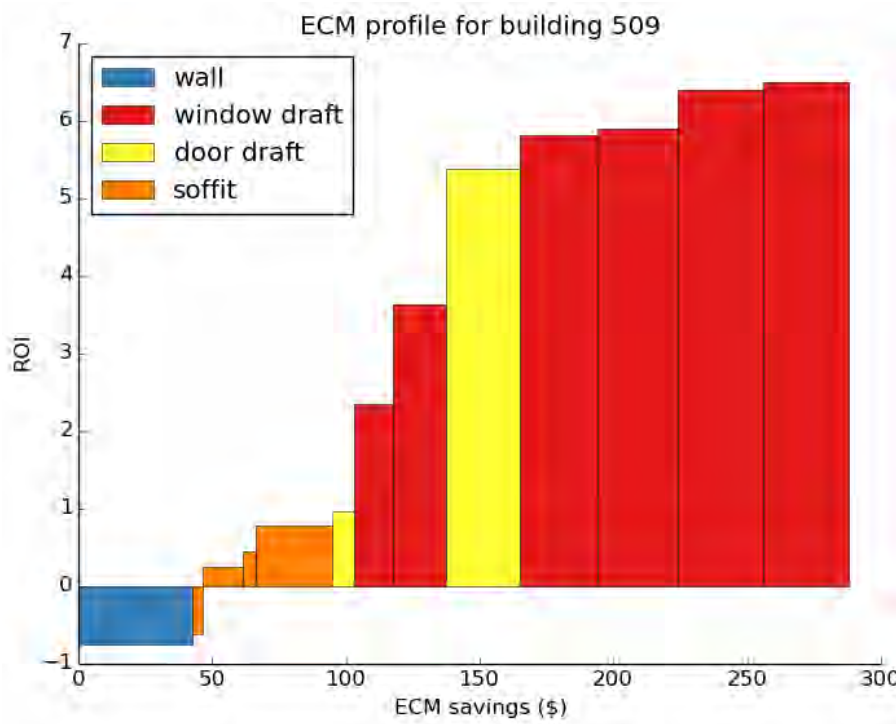


Table D-26 lists the recommended envelope ECMs for Bldg 509, Camp Lejeune.

Table D-26. Envelope ECMs for Bldg 509, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Window Frame Leaks	248	243	157	388	2.5
Improve Soffit Insulation	76	75	49	476	9.8
Seal Door Frame Leaks	57	55	36	129	3.6

Annual potential remediation savings for this building are \$242 and total payback is 4.1 years for envelope-related ECMs.

## D.27 Bldg 895

### D.27.1 Description of Bldg 895, Marine Corps Base Camp Lejeune, NC

**Name:** Administrative Office

**Use Type:** Misc.

**Square Footage:** 16,782

**Avg. Daily Electric Use:** 877.7 kWh

**Electricity Score:** 70th Percentile

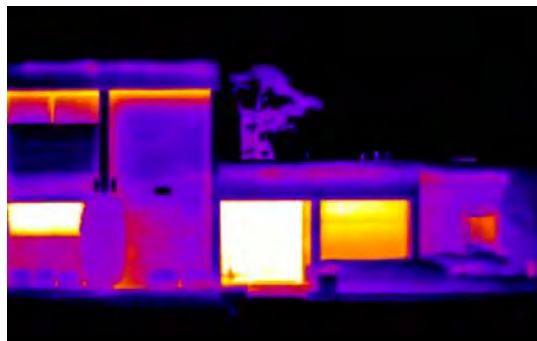
**Electricity Usage:** 19.1 kWh/sq ft/yr.

Figures D-121 and D-122, respectively, show the aerial view and thermal image of Bldg 895, Camp Lejeune.

Figure D-121. Aerial view of Bldg 895, Camp Lejeune.



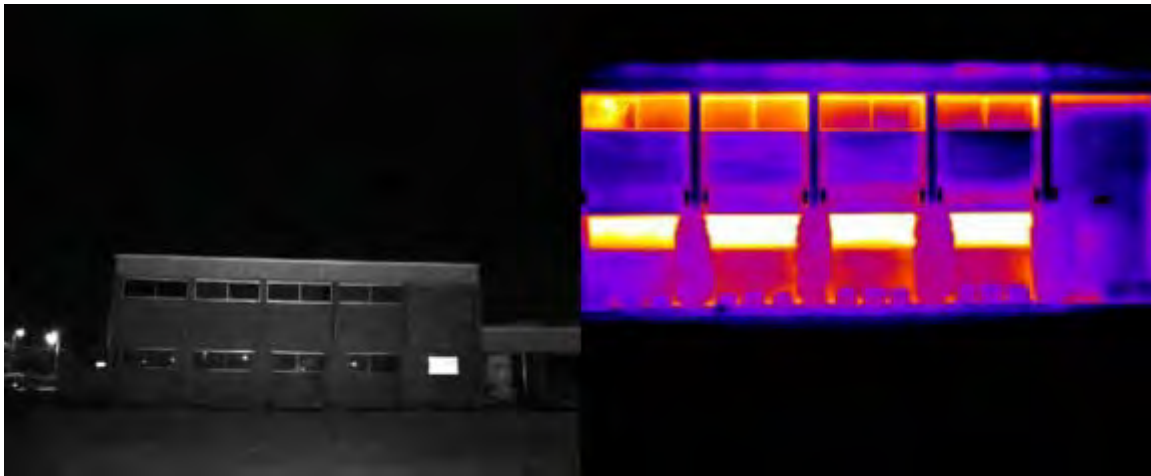
Figure D-122. Thermal image of Bldg 895, Camp Lejeune.



### D.27.2 Notable leaks at Bldg 895, Marine Corps Base Camp Lejeune, NC

The windows of Bldg 895 are quite a bit more emissive than any other windows that were scanned on the base. They can be seen at timestamp 135:44 (Figure D-123).

Figure D-123. NIR image (left) and thermal image (right) of Bldg 895, Camp Lejeune.



### D.27.3 Envelope ECMs for Bldg 895, Marine Corps Base Camp Lejeune, NC

Figure D-124 shows the relative ROI for envelope ECMs for Bldg 895, Camp Lejeune.

Figure D-124. ECM profile for Bldg 895, Camp Lejeune.

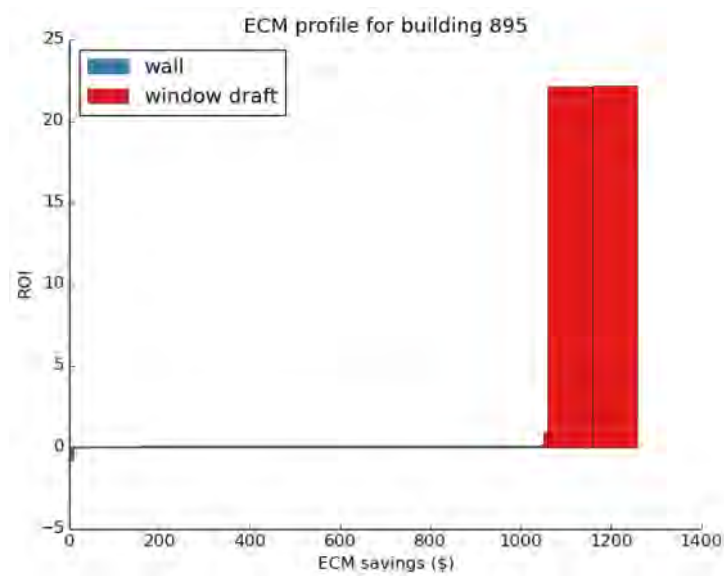


Table D-27 lists the recommended envelope ECMs for Bldg 895, Camp Lejeune.

Table D-27. Envelope ECMs for Bldg 895, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1631	1597	1034	14135	13.7
Seal Window Frame Leaks	591	579	217	324	1.5

Annual potential remediation savings for this building are \$1,251 and total payback is 11.6 years for envelope-related ECMs.

## D.28 Bldg 2603

### D.28.1 Description of Bldg 2603, Marine Corps Base Camp Lejeune, NC

**Name:** Barracks

**Use Type:** Multifamily

**Square Footage:** 14,237

**Avg. Daily Electric Use:** 400 kWh

**Electricity Score:** 65th Percentile

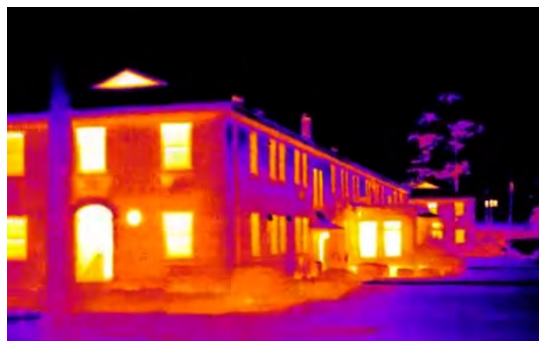
**Electricity Usage:** 10.3 kWh/sq ft/yr.

Figures D-125 and D-126, respectively, show the aerial view and thermal image of Bldg 2603, Camp Lejeune.

Figure D-125. Aerial view of Bldg 2603, Camp Lejeune.



Figure D-126. Thermal image of Bldg 2603, Camp Lejeune.



### D.28.2 Notable leaks at Bldg 2603, Marine Corps Base Camp Lejeune, NC

The wall at timestamp 221:37 is poorly insulated, with a notable hot spot above the door frame (Figure D-127).



Figure D-127. NIR image (left) and thermal image (right) of Bldg 2603, Camp Lejeune.



### D.28.3 Envelope ECMs for Bldg 2603, Marine Corps Base Camp Lejeune, NC

Figure D-128 shows the relative ROI for envelope ECMs for Bldg 2603, Camp Lejeune.

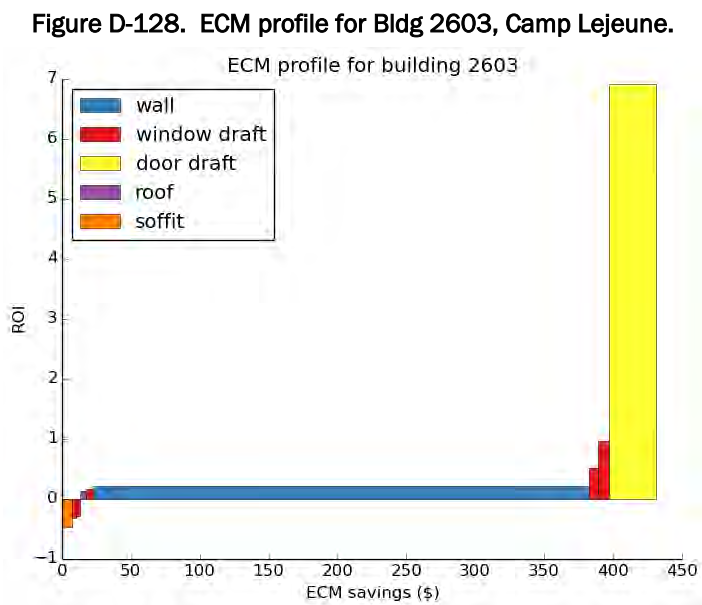


Table D-28 lists the recommended envelope ECMs for Bldg 2603, Camp Lejeune.

Table D-28. Envelope ECMs for Bldg 2603, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	568	556	360	4470	12.4
Seal Door Frame Leaks	54	52	34	64	1.9
Seal Window Frame Leaks	41	40	26	323	12.5

Annual potential remediation savings for this building are \$420 and total payback is 11.6 years for envelope-related ECMs.

## D.29 Bldg HP285

### D.29.1 Description of Bldg HP285, Marine Corps Base Camp Lejeune, NC

**Name:** Barracks

**Use Type:** Multifamily

**Square Footage:** 47,709

**Avg. Daily Electric Use:** 1063 kWh

**Electricity Score:** 30th Percentile

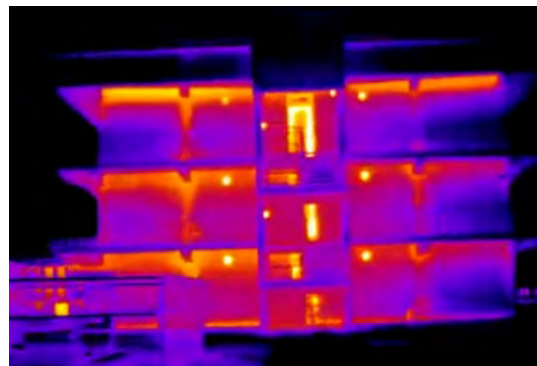
**Electricity Usage:** 8.1 kWh/sq ft/yr

Figures D-129 and D-130, respectively, show the aerial view and thermal image of Bldg HP285, Camp Lejeune.

Figure D-129. Aerial view of Bldg HP285, Camp Lejeune.



Figure D-130. Thermal image of Bldg HP285, Camp Lejeune.

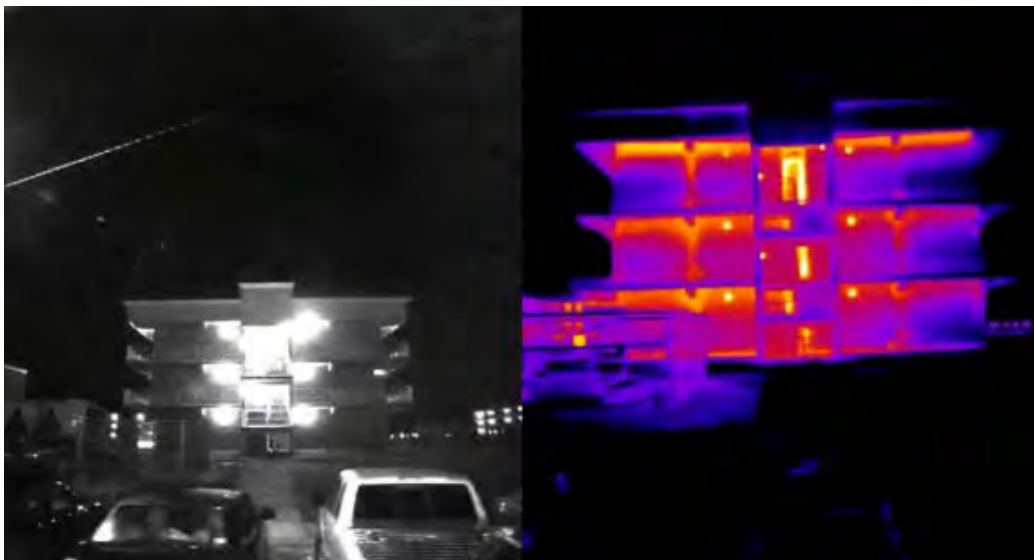


### D.29.2 Notable leaks at Bldg HP285, Marine Corps Base Camp Lejeune, NC

The walls and door shown at timestamp 118:23 are notable emissive (Figure D-131).



Figure D-131. NIR image (left) and thermal image (right) of Bldg HP285, Camp Lejeune.



### D.29.3 Envelope ECMs for Bldg HP285, Marine Corps Base Camp Lejeune, NC

Figure D-132 shows the relative ROI for envelope ECMs for Bldg HP285, Camp Lejeune.

Figure D-132. ECM profile for Bldg HP285, Camp Lejeune.

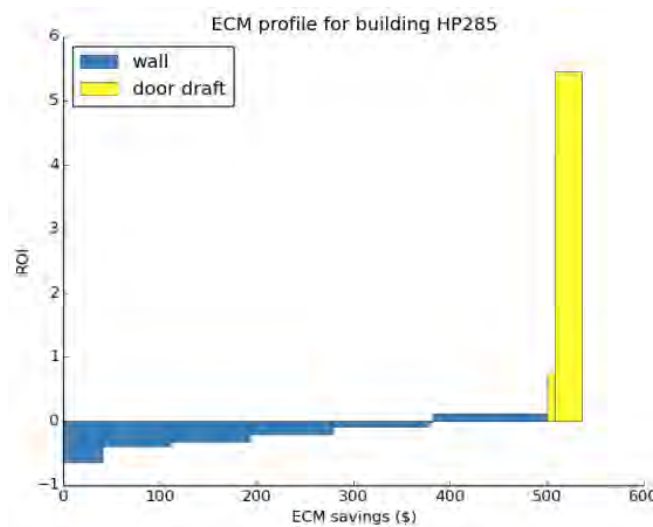


Table D-29 lists the recommended envelope ECMs for Bldg HP285, Camp Lejeune.

Table D-29. Envelope ECMs for Bldg HP285, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	720	705	456	8390	18.4
Seal Door Frame Leaks	62	61	39	193	4.9

Annual potential remediation savings for this building are \$496 and total payback is 17.3 years for envelope-related ECMs.

## D.30 Bldg HP507

### D.30.1 Description of Bldg HP507, Marine Corps Base Camp Lejeune, NC

**Name:** Barrack

**Use Type:** Multifamily

**Square Footage:** 42,090

**Avg. Daily Electric Use:** 1,027 kWh

**Electricity Score:** 65th Percentile

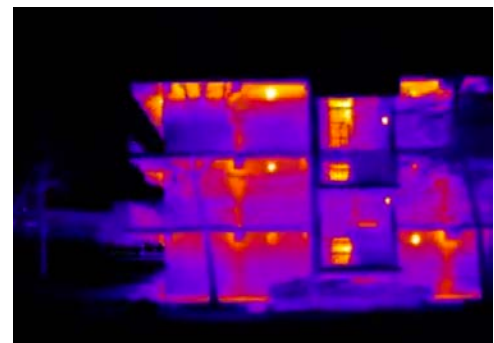
**Electricity Usage:** 8.9 kWh/sq ft/yr.

Figures D-133 and D-134, respectively, show the aerial view and thermal image of Bldg HP570, Camp Lejeune.

Figure D-133. Aerial view of Bldg HP507, Camp Lejeune.



Figure D-134. Thermal image of Bldg HP570, Camp Lejeune.



### D.30.2 Notable leaks at Bldg HP507, Marine Corps Base Camp Lejeune, NC

The walls at timestamp 160:11 show a similar highly emissive pattern, with heat loss both at the top and down the middle of each wall (Figure D-135).

Figure D-135. NIR image (left) and thermal image (right) of Bldg HP507, Camp Lejeune.



### D.30.3 Envelope ECMs for Bldg HP507, Marine Corps Base Camp Lejeune, NC

Figure D-136 shows the relative ROI for envelope ECMs for Bldg HP570, Camp Lejeune.

Figure D-136. ECM profile for Bldg HP507, Camp Lejeune.

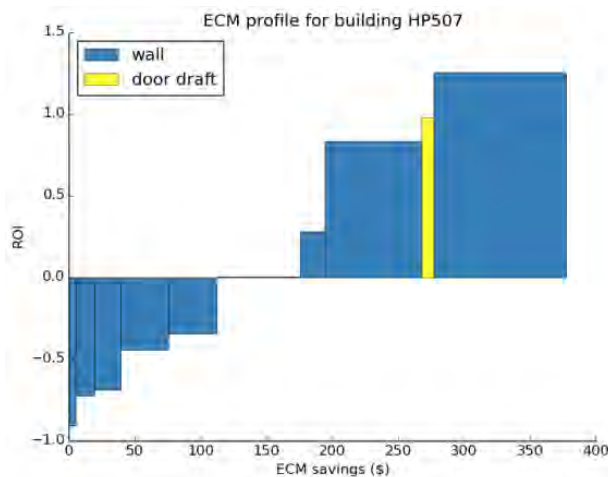


Table D-30 lists the recommended envelope ECMs for Bldg HP570, Camp Lejeune.

Table D-30. Envelope ECMs for Bldg HP570, Camp Lejeune.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	520	509	329	4257	12.9

Annual potential remediation savings for this building are \$329 and total payback is 12.9 years for envelope-related ECMs.

## Appendix E: Remediation Cost Estimates

This appendix provides details on the approaches used to estimate mitigation costs associated with window frame sealing, door frame sealing, wall insulation, and roof insulation. For the purposes of this analysis, it was assumed that soffit insulation shares the same characteristic costs as roof insulation, as soffit-specific remediation costs were not readily available. All of these calculations use a standard labor cost per hour,  $L_{cost}$ , which is assumed to be \$60.

### E.1 Window frame sealing

The cost of window frame sealing can be modeled as:

$$C_w = W_{num} \cdot M_{window} + L_{cost} \cdot \frac{W_{time}}{60} \quad (E-1)$$

where:

$W_{num}$  is the number of windows sealed  
 $M_{window}$  is the material cost per window sealed, assumed to be \$33<sup>[1]</sup>  
 $W_{time}$  is the labor time required per window sealed, assumed to be 37 minutes.<sup>[1]</sup>

This resulted in a typical window sealing cost of \$70 per window, assuming that enough windows will be sealed during a single trip that other time costs (e.g., travel time) will be negligible.

### E.2 Door frame sealing

Doorframe sealing and weather-stripping is calculated similarly to window frame sealing:

$$C_d = D_{num} \cdot \left( M_{door} + L_{cost} \cdot \frac{D_{time}}{60} \right) \quad (E-2)$$

where:

$D_{num}$  is the number of doors sealed  
 $M_{door}$  is the material cost per door sealed, assumed to be \$14.9<sup>[2]</sup>  
 $D_{time}$  is the labor time required per door sealed, assumed to be 57 minutes.<sup>[2]</sup>

This results in a typical door sealing/weather-stripping cost of \$72 per door.

### E.3 Wall insulation

Wall insulation costs are comprised of access time, installation time, insulation costs, and other material costs related in the equation below:

$$C_w = W_{sqft} \cdot M_{wall} + L_{cost} \cdot \left( \frac{W_{sqft}}{W_{rate}} \right) \quad (E-3)$$

where:

- $W_{sqft}$  is the square footage of the wall in question
- $M_{wall}$  is the material cost per square foot of insulation installed, assumed to be \$2.87<sup>[3]</sup>
- $W_{rate}$  is the square footage of wall insulation that can be installed in an hour by a single worker, including preparation and access time, assumed to be 13.<sup>[3]</sup>

For a 100 sq ft section of poorly insulated wall, this would amount to a total cost of \$784.

### E.4 Roof insulation

Roof insulation costs are calculated similarly to wall insulation costs, and are comprised of access time, installation time, insulation costs, other material costs, and fixed material costs related in the equation below:

$$C_r = R_{sqft} \cdot M_{roof} + L_{cost} \cdot \left( \frac{R_{sqft}}{R_{rate}} \right) \quad (E-4)$$

where:

- $R_{sqft}$  is the square footage of the wall in question
- $M_{roof}$  is the material cost per square foot of insulation, assumed to be \$2.66.<sup>[4]</sup>
- $R_{rate}$  is the square footage of roof/ceiling insulation that can be installed in an hour by a single worker, including preparation and access time, assumed to be 11.5.<sup>[3]</sup>

For a 100 sq ft section of poorly insulated roof, this would amount to a total cost of \$788.

## E.5 References

1. Homewyse. 2014. Cost to Seal Windows – 2014 Cost Calculator. Available: [http://www.homewyse.com/services/cost\\_to\\_seal\\_windows.html](http://www.homewyse.com/services/cost_to_seal_windows.html)
2. Homewyse. 2014. Cost to Seal Doors – 2014 Cost Calculator. Available: [http://www.homewyse.com/services/cost\\_to\\_seal\\_door.html](http://www.homewyse.com/services/cost_to_seal_door.html)
3. Pacific Northwest National Laboratory. 2011. Advanced Energy Retrofit Guide — Office Buildings. Insulate Walls Measure, pages 153-154.
4. Pacific Northwest National Laboratory. 2011. Advanced Energy Retrofit Guide — Office Buildings. Insulate Roof Measure, pages 154-155.

## Appendix F: Collected Data Sample

Data Description: Essess collected terabytes of data at each base. Below is an example summary data file for 14 seconds of Essess data. Green text is the system data file and the black text is the explanation of what was actually happening in the system.

```

Sample Data:
path: 2014-02-22-19-16-22_7.bag
version: 2.0
duration: 14.0s
start: Feb 22 2014 19:16:22.46 (1393114582.46)
end: Feb 22 2014 19:16:36.50 (1393114596.50)
size: 2.0 GB
/diagnostics
System Diagnostic Information
/driver_bottom_camera/camera_info
Camera Information & Intrinsics
/driver_bottom_camera/color_remapped
8bit color image remapped from 16bit mono image data
/driver_bottom_camera/flir_info
FLIR thermal coefficients and hardware information
/driver_bottom_camera/image_info
Image Statistics
/driver_bottom_camera/image_raw
Raw 16bit Image Data
/driver_bottom_camera/image_raw_throttle
2Hz Throttled Raw 16bit Image Data
/driver_nir/camera_info
Camera Information & Intrinsics
/driver_nir/hardware_info
Camera hardware information
/driver_nir/image_info
Image Statistics
/driver_nir/image_raw
Raw 16bit Image Data
/driver_nir/image_raw_throttle
2Hz Throttled Raw 16bit Image Data

```

/driver\_nir/reduced\_and\_throttled  
2Hz Throttled 8bit Image at half resolution  
/driver\_top\_camera/camera\_info  
/driver\_top\_camera/color\_remapped  
/driver\_top\_camera/flir\_info  
/driver\_top\_camera/image\_info  
/driver\_top\_camera/image\_raw  
/driver\_top\_camera/image\_raw\_throttle  
See /driver\_bottom\_camera  
/environmental\_data  
Internal and External ambient temperature sensors  
/lidar\_sick/hw\_info  
2D LIDAR Hardware Information  
/lidar\_sick/scan  
2D LIDAR scan data  
/passenger\_bottom\_camera/camera\_info  
/passenger\_bottom\_camera/color\_remapped  
/passenger\_bottom\_camera/flir\_info  
/passenger\_bottom\_camera/image\_info  
/passenger\_bottom\_camera/image\_raw  
/passenger\_bottom\_camera/image\_raw\_throttle  
See /driver\_bottom\_camera  
/passenger\_nir/camera\_info  
/passenger\_nir/hardware\_info  
/passenger\_nir/image\_8bit  
/passenger\_nir/image\_info  
/passenger\_nir/image\_raw  
/passenger\_nir/image\_raw\_throttle  
/passenger\_nir/reduced\_and\_throttled  
See /driver\_nir  
/passenger\_top\_camera/camera\_info  
/passenger\_top\_camera/color\_remapped  
/passenger\_top\_camera/flir\_info  
/passenger\_top\_camera/image\_info  
/passenger\_top\_camera/image\_raw  
/passenger\_top\_camera/image\_raw\_throttle  
See /driver\_bottom\_camera  
/rosout  
/rosout\_agg  
ROS Diagnostic logging



/tf  
Geometric transformation information  
    /trimble/hw\_info  
Trimble GPS Information  
    /trimble/nav\_sat\_fix  
Trimble GPS position  
    /trimble/nav\_sat\_fix\_fast  
High rate Trimble GPS position estimate  
    /trimble/raw  
Trimble GPS raw data  
    /trimble/temperature  
Trimble GPS case temperature  
    /velodyne/fix  
Velodyne LIDAR integrated GPS position  
    /velodyne/hw\_info  
Velodyne LIDAR hardware information  
    /velodyne/imu  
Velodyne LIDAR integrated IMU  
    /velodyne/nmea  
Velodyne raw NMEA GPS data  
    /velodyne/temp  
Velodyne case temperature  
    /velodyne/time\_reference  
Velodyne time reference  
    /velodyne/vel  
Velodyne velocity estimate from integrated GPS  
    /velodyne\_ins/raw  
Raw Velodyne inertial navigation data  
    /velodyne\_packets  
Raw Velodyne LIDAR data  
    /velodyne\_points  
Pointcloud data

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14. ABSTRACT Each year, U.S Department of Defense buildings waste millions of dollars' in energy lost through leaks in building envelopes. Identifying the source of this wasted energy has historically been time consuming and prohibitively expensive for large-scale energy analysis. This work used an independently developed drive-by thermal imaging solution that can enable the Department of Defense (DoD) to achieve cost-effective energy efficiency at much greater scale than other commercially available techniques of measuring energy loss due to envelope inefficiencies from the built environment. A multi-sensor hardware device is attached to the roof of a customized vehicle to rapidly scan hundreds of buildings in a short period of time. At U.S. Marine Corps Base Camp Lejeune, the unit identified over 2500 distinct building feature components identified across various buildings throughout the base. These features were categorized by type and surface temperature to provide an in-depth analysis of each building's envelope energy profile. This report includes an in-depth analysis of 30 buildings at each installation, recommends specific energy conservation measures (ECMs), and quantifies significant potential return on investment.					
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